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POWER SPECTRUM ANALYSIS OF CLIMATOLOGICAL DATA FOR WOODSTOCK COLLEGE, MARYLAND

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ABSTRACT

Power spectrum techniques are applied to series of daily, weekly, and monthly average temperature and precipitation values, recorded since 1870 at the Woodstock Climatological Benchmark Station in Maryland, in order to gain a reasonable interpretation of the extent and frequency distribution of periodic variations in these data. Analysis procedures are outlined, and the results presented, interpreted, and collated with the results of earlier literature in some detail.

Apparent short-period variations are found whose periods lie near 3 days, between 5 and 7 days, and between about 15 and 25 days; various of them however, are absent from some portions of the data series and also differ somewhat in character with the season of the year.

Significant long-period variations are more prevalent in the temperature series than in the precipitation series. Spectral peaks in temperature, of periods near 2 years and greater than 50 years, both achieve high levels of statistical significance. The 11-year sunspot cycle, and to some extent its second harmonic as well, is suggested in the temperature data. The double (22-year) sunspot cycle and the longer Brückner cycle, however, are almost totally absent. The basis of Abbot's statistical long-range prediction scheme, which utilizes numerous higher harmonics of the double sunspot cycle, is tested against the Woodstock data, and is found in this case to lack measurable skill above chance.

1. INTRODUCTION TO PROBLEMS OF WEATHER PERIODICITIES

The notion of periodic phenomena in weather conditions is probably as old as mankind. The scientific search for such cyclic elements in weather and climate dates back to the days of the first instrumental observations of atmospheric events. The underlying idea was borrowed from astronomy. In celestial mechanics it had been eminently successful to resolve the complicated motions of the sun, the moon, and the planets into *ephemerides* which predicted with high accuracy their positions, movements, and occultations. The early scientists tacitly concluded that the weather must be arranged in some lawful order also: why not analyze it the same way as planetary observations? Thus the almanac was born with its juxtaposition of celestial and weather predictions.

But weather did not quite fit the pattern. Thus ever since the middle of the 18th century studies on cycles in the atmosphere have accumulated. Some exhibit wishful thinking, many others are serious. One of the most recent extensive studies (Berlage [7]), dealing with cycles over one year in length, lists 55 periods ranging from 1.03 to 36

years. These have been proclaimed by various investigators as present in meteorological data series. Berlage lists over 350 references, nearly all of them in the literature of the current century. Numbers of the same order of magnitude could be given for cycles in the shorter time interval of less than one year. It is interesting to note that most modern writers in the field refer to *hidden* periodicities. This implicitly admits that the regular variations are masked by meteorological "noise", or apparently random fluctuations. But authors of pertinent papers have made more or less modest claims for the forecasting value of alleged periodicities (Wing [38]). In some recent writings this has led to attempts at extrapolation into the future of long rainfall series in the Middle West and Southwest of the United States (Abbot [1]).

What reasoning maintains the belief in weather cycles? Most important is, of course, the actual presence of a few atmospheric periodicities. The diurnal and annual variations produced by axial rotation of the earth and the planet's revolution around the sun are so pronounced in their effects that it seems almost superfluous to mention them. In these cases an overwhelming "forcing function" is operative and results can be readily expressed as harmonic elements in the diurnal and annual march of most meteorological variables. Also present, without doubt but with infinitesimally smaller amplitude, are periodic manifestations of lunar tidal forces in the atmosphere. In fact, it took considerable scientific detective work to discover the true lunar gravitational tides. Their effect on pressure is generally only a fraction of a millibar (Chapman [10]). As in any mechanical system one should also expect in the atmosphere free oscillations. These are primarily governed by the vertical temperature distribution and stratification. Their order of magnitude is from fractions of an hour, in a local setting, to fractions of a day for the whole atmospheric layer.

Interestingly enough, the kinematics of the atmospheric circulation produces other quasi-periodic elements in the field of atmospheric motions. For shorter time intervals of a few days these have been made theoretically plausible (Rossby [26], Haurwitz [16]). Somewhat longer cyclical elements also become apparent in the calculations involving simplified theoretical models of the general circulation (Smagorinsky [31]).

Somewhat overlooked in recent years have been the suggestions that the arrangement of the subtropical anticyclones indicates fairly stable vorticity concentrations, which in turn could produce periodic oscillations (Stewart [32]). Rough estimates of the normal modes of such oscillations give the wide brackets of 2,000 to 5,000 days and 70,000 to 250,000 days. The arrangement of the fixed geographical features of the earth also suggests that there would be an induction of periodic elements into atmospheric motions, both on a small and a large scale.

Probably the widest discussion has ranged over the possibility of forced fluctuations in atmospheric parameters because of variable solar radiation. These have been primarily associated with the solar period of rotation of 27 days and the irregular sunspot rhythm of 11.3 years, its fractions and its multiples. The tantalizing circumstance here is that there are close correlations between the solar conditions and the ionospheric responses. But a strong link to the lower atmosphere has still to be forged. The best one can say is that some evidence of solar influences, other than the diurnal and annual, exists. But these influences wax and wane quite irregularly. Typical of the results obtained is a recent analysis of the 27-day cycle in terrestrial temperature data for limited intervals by Visser [36].

Berlage [6, 7] in his comprehensive treatises tries to make a case for a combination of solar and terrestrial factors leading to the multiplicity of observed periodicities. A primary element in his system is the late Sir Gilbert Walker's *Southern Oscillation*. This is the fluctuation of the pressure difference between the Malayan Archipelago and Easter Island. It is argued that this is a primary terrestrial period of $2\frac{1}{3}$ (2 to 3) years, caused by mutual interactions of air and sea temperatures, the latter influenced by oceanic currents. Lower harmonics of this "cycle", 5 and ~7 years, then show interference with solar cycles (say perhaps, $5.6=\frac{1}{2}$, $11.3=1$, $23=2$ solar periods). This leads to beat frequencies and the confusing welter of meteorological time series. Other basic cycles might, of course, participate in the merry rhythm dance.

It is, therefore, understandable that a great deal of cycle research has been undertaken essentially in quite an empirical fashion, with the hope of first obtaining statistically significant results and then, if possible, of tying these to some plausible physical cause. Most of these studies have used some form of harmonic or periodogram analysis. A review of the findings which are based on reasonably adequate statistical procedures reveals as the most universal rhythms the following: $2\frac{1}{3}$, $3\frac{1}{3}$, 5–6, 11–12, 19–24, and 30–35 years in length (Landsberg [18]).

The longer the span the more irregular is the interval between extremes. These rhythms were, however, noted in such diverse elements as pressure, temperature, precipitation, lake levels, temperature range, and extreme weather conditions in series of observations originating at such distant points as North America, Central and Eastern Europe, and Indonesia.

Panofsky and McCormick [24] have stated, "Direct harmonic analysis yields a number of harmonics equal to half the number of observations. The amplitude of these harmonics oscillates wildly from one harmonic to the next. These oscillations are not reproducible from one time series to another which has basically the same statistical properties. We, therefore, need to compute a smooth spectrum. The autocorrelation method with the number of lags small compared to the number of observations yields a smooth spectrum directly with a great deal less

numerical work than would be required for computing and smoothing the spectral estimate obtained by direct Fourier analysis."

It is always good scientific practice to use new procedures and additional data to probe into unresolved puzzles. For time series of rapidly fluctuating elements power spectrum analysis has become a widely accepted technique to separate "signals" from "noise." In meteorological series this tool has been primarily used for short-period phenomena, such as turbulent wind fluctuations. It has gradually found its entry into analysis of wave motions on a hemispheric-synoptic scale. We will attempt to extend its use here to climatic series. As object of this analysis we have chosen the climatic reference station at Woodstock, Md. For this station daily, weekly, and monthly temperature and precipitation values are available for analysis, covering the period from 1870–1956. Most of the data are in machine-processable form.

2. BASIC DATA

STATION SELECTION AND QUALITY

Woodstock, Md., is located about 16 miles west-northwest of Baltimore at 39°20′ N., 76°53′ W. Climatological records have been maintained there virtually without interruption since 1870. The length and quality of these records, evident stability of station location in the more recent years, apparent freedom from environmental influence and change, and good prospects of future record continuity, have qualified Woodstock as a member of the Weather Bureau's Climatological Benchmark Network.

Records since 1893 of monthly mean temperature and total precipitation for Woodstock have been subjected to a rigorous analysis of homogeneity. The analysis has revealed two discontinuities in temperature which were evidently associated with undocumented station moves about March 1901 and about January 1914. Between 1901 and 1914, mean temperatures were registering about 2.5° F. too high in winter and about 1.5° F. too high in summer, relative to the record since 1914. The record prior to 1901 was approximately homogeneous with the record since 1914. The analysis also indicates that the precipitation record is homogeneous, with the possible exception of a period of several years between 1930 and 1940, when the gage catch at Woodstock was apparently deficient by about 6 percent.

Since the nature of the temperature inhomogeneity is rather confidently known, the relative imprecision of the spectrum analysis (at long wavelengths) can be estimated (see section 4). Other inhomogeneities which may exist in the temperature and precipitation series are evidently so small that, in the writers' opinion, they are incapable of affecting the spectra based on those series to a significant degree.

DATA PROCESSING

The existence of preferred group periods over as long a time interval as possible in both precipitation and temperature records was chosen for investigation. Monthly as well as daily values were selected for analysis. Early in the investigation it was decided that lag periods of more than 100 would be used. The maximum lag period of the then available IBM 650 Bell Laboratory spectrum analysis routine was 100. Therefore, plans were made to make a new program. Actually, it was necessary to make two new programs due to the relatively small magnetic memory drums of the IBM 650, 2,000 words. One of the programs developed will handle lag periods from 0 to 400 while the other will handle lag periods from 400 to 750.

Experience gained in processing data indicated that memory dump routines would be required. Therefore, such routines were made for use during either the input of data or output of information. The memory was "dumped" every hour. This took only about two minutes, but always provided a new starting point if any malfunction occurred in equipment or power. Such a procedure also bypassed the necessity of remaining with the problem until all computation was finished. In other words, work on this project could be curtailed for priority work or stopped at the end of a shift and started again the next day.

This is important, for with large amounts of input data and large lag, input and output rates may be reduced to two cards per minute.

DATA CARD DECKS

The input data to the machines were in punched card form. The data required for this particular study were daily and monthly values of the average temperatures and total precipitation. The average temperatures were measured in ° F. and the total precipitation in inches.

Daily data, 1895–1956.—Daily values of maximum, average, and minimum temperatures and precipitation were sought. Although inferences indicated the existence of daily data back to 1875, investigation failed to find them. Prior to 1910 there were breaks in the record, usually in the summertime. It was necessary to devise methods of interpolation of the missing observations. Even with these, it was deemed inappropriate to fill in the gap periods prior to 1895 because these gaps began to exceed two months.

To obtain the values to be substituted for missing data, comparisons with nearby stations' observations were made. In general, the curves of daily values of the elements were constructed by standard methods of interpolation and the required values were obtained.

Monthly data, 1875–1956.—Monthly averages of maximum, average, and minimum temperatures and of precipitation could be interpolated much more easily, and for this reason the period could be extended back to 1875. In a test group of cases where monthly values

were computed and compared with observed values, the differences between observed and interpolated were all less than $\pm 0.5°$ F.; generally, their magnitude was near $\pm 0.1°$ F. Thus, there is reasonable assurance that the interpolated values used should not be far from the values which would have been recorded. The monthly precipitation totals were transformed by the equation

$$Y=\sqrt{X}+\sqrt{X+1} \tag{1}$$

where X is the monthly total precipitation [14].

3. PROCEDURES

Tukey's paper [35] which deals with the sampling theory of power spectrum analysis is used as the basis of this study. His subsequent papers as co-author with Blackman [8] have also been utilized. The formulas given here, in essence, are those of Tukey with the following exceptions:

a. The total overall mean is used to determine all serial products rather than the mean for the individual lag interval (see Panofsky and Brier [23]).

b. Division of all covariances by the initial covariance permits the immediate computation of normalized line powers. However, when the data are plotted in this form, the variance at zero lag is not readily available. The formulas used are as follows:

(*i*) Serial Products

$$SP=\sum_{i=1}^{n-p}(X_i-\overline{X})(X_{i+p}-\overline{X}); \tag{2}$$

$$\overline{X}=(1/n)\sum_{i=1}^{n}X_i \tag{3}$$

where p is the lag and n is the number of observations in the entire sample.

(*ii*) Mean Serial Product or Covariances

$$R=SP/(n-p) \tag{4}$$

(*iii*) Covariance Ratio

$$R/R_0=R';\ R_p/R_0=R'_p;\ 0<p<m \tag{5}$$

(*iv*) Line Powers

$$L_0=(1/2m)(R'_0+R'_m)+(1/m)\sum_{p=1}^{m-1}R'_p \tag{6}$$

$$L_h=(1/m)R'_0+(2/m)\sum_{p=1}^{m-1}R'_p\cos ph\pi/m+(1/m)R'_m\cos h\pi \tag{7}$$

$$L_m=(1/2m)(R'_0+(-1)^mR'_m)+(1/m)\sum_{p=1}^{m-1}(-1)^pR'_p \tag{8}$$

where m is the maximum lag.

$$0\leq p\leq m-1$$

$$0\leq h\leq m-1$$

(*v*) Smoothing Formulas (after Hamming and Tukey [15])

$$U_0=0.54L_0+0.46L_1 \tag{9}$$

$$U_k=0.54L_k+0.23(L_{k-1}+L_{k+1});\ 0<k<m \tag{10}$$

$$U_m=0.54L_m+0.46L_{m-1} \tag{11}$$

4. RESULTS

SHORT-PERIOD VARIATIONS

For the precipitation fluctuations in the range from 2 days to a month analyses were run for several 5-year intervals. Results for four of these intervals, namely 1910–14, 1941–45, 1946–50, and 1951–55 are shown in figure 1. For the interval 1951–55 the daily temperature data were also analyzed. Their power spectra are depicted in figure 2. The first impression one gets from the curves is one of variety. None of the periods is outstanding. Each of the chosen intervals seems to have its own spectrum. Nonetheless there are some interesting features. In figure 1 these are represented by three lines. The first is around 3 days, the second between 5 and 7 days, and the third in the 15- to 25-day span. In the temperature curves (fig. 2), which represent only one 6-week season, the winter, the 5- to 7-day periods are quite pronounced. There is also some power in the longer intervals over 20 days. Even though these periods are not distinctly fixed and vary markedly from year to year they undoubtedly reflect a physical mechanism in the atmosphere.

The 3-day period is apparently associated with a fast-moving wave around the globe. There are hints of that type of phenomenon in the literature. Portig [25] has called attention to such a rapid pressure wave. Very little is known about the nature of this wave. Angell [2] noted a peak in variance when he analyzed wind fluctuations at the 300-mb. level for an interval of 50 hours. This is a little shorter than the 3-day peak at Woodstock but Angell's data were primarily from the Pacific area.

The 5- to 7-day interval prominence in the power spectrum confirms age-old meteorological knowledge. It may be useful to cite some of the classical findings here. Arctowski [3] in the results of the Belgica Expedition (1897–99) mentioned that the pressure waves near the Antarctic had an average duration of 5 days 6 hours. Meinardus [20] from the data of the German South Polar Expedition (1901–03) noted an average length of pressure waves of 5 days 2 hours. For the data of the Scott Expedition, Simpson [30] calculated the following periods for the Southern Hemisphere and the Antarctic coast:

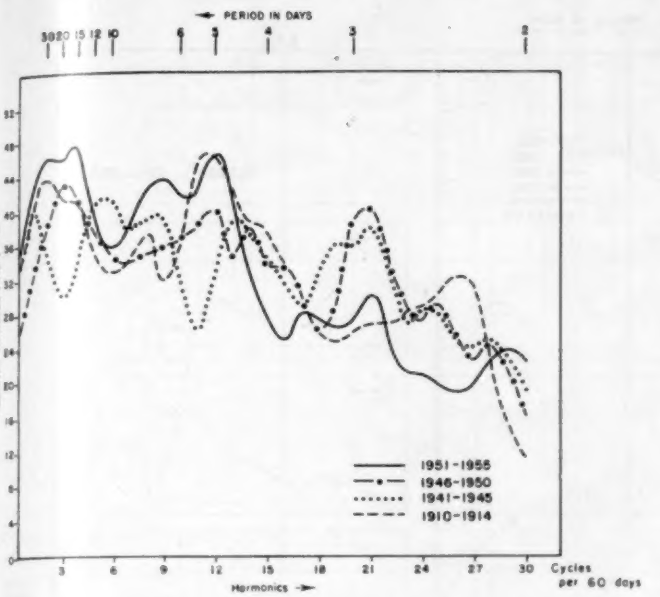

Figure 1.—Power spectrum analysis of daily precipitation data, Woodstock College, Md. Maximum lag is 30. The sum of the 30 relative variances equals 1 or 100 percent.

Latitude	*1st*	*2d*	*3d*	*4th*	*wave*
52° S	3. 65	7. 32	13. 48	29. 5	*days*
70° S	3. 39	6. 06	13. 43	43. 1	*days*

In the Northern Hemisphere A. Wegener [37] found for East Greenland for the year, less the summer months, an average duration of pressure waves of 5.6 days. In the summer the pressure fluctuation lengthened to a 9.4-day period. The 5.6-day pressure wave was also noted by Merecki [21, 22] in Warsaw. In Western Europe L. Descroix [13] described a 5-day period for Paris, and Scoles [28] found the same periodicity in the data for Malta during April. In the August to September season that Mediterranean island showed an 8.2-day fluctuation. H. H. Clayton [11] also propounds 3.5- to 5-day pressure periodicities. In a very careful harmonic analysis A. Defant [12] finds the following waves in precipitation data in the middle latitudes of the two hemispheres:

Latitude	*1st*	*2d*	*3d*	*4th*	*wave*
35° S	7. 2	12. 1	16. 6	31. 2	*days*
45° N	5. 7	8. 7	12. 7	24–25	*days*

The physical explanation of the 5- to 7-day periodicity pattern seems to be closely related to the long waves in the westerlies, first described by Rossby. In a 4-wave system with a movement of 18° longitude per day one revolution of the whole wave train would take, for example, 20 days so that a fixed point on the surface would experience a wave passage once every 5 days. In a 3-wave system one passage per 7 days would be noted (cf., in this connection, Saltzman [27]). In the subtropical easterly currents similar wavelengths seem to be prevalent. Hubert [17] noted that the lag correlation for the thickness of the 1000- to 700-mb. layer had a 5-day maximum of 0.7 at San Juan, Puerto Rico.

We may also recall here the rediscovery of the 7-day cycle in connection with the controversial periodic cloud seeding experiments (Langmuir [19], Brier [9]).

The importance such periodicities may have for extended forecasting by numerical procedures has been stressed by Scorer [29]. The unfortunate circumstance is the rather flexible lengths of rhythms—and, as our spectra show, the rather wide variations from year to year. Little is known yet as to what elements determine the wave number in the atmospheric currents. There are some relations to the large oceanic heat sources in winter but what causes changes from a 3-wave to a 4- or more wave system is still a mystery.

The seasonal variability found by others for the short-periodic rhythms made it appear worthwhile to try power spectrum analysis for a few years by seasons. In doing this we adopted the meteorological seasons advocated by Baur [4,5] for the middle latitudes of the Northern Hemisphere. He adduces important arguments that the chosen intervals are in their circulation patterns more homogeneous than the customary 3-month seasons. His intervals are 45 or 46 days long and comprise the following dates:

Season 1: January 1–February 14 (High winter)
2: February 15–March 31 (Pre-spring)
3: April 1–May 16 (Full spring)
4: May 17–June 30 (Pre-summer)
5: July 1–August 15 (High summer)
6: August 16–September 30 (Early autumn)
7: October 1–November 15 (Main autumn)
8: November 16–December 31 (Pre-winter)

The graphs of figure 3 show the power spectra for the daily precipitation at Woodstock College, Md., for each of the years 1951–55. At first glance these show little consistency. Although the non-normal distribution of the precipitation data raises doubts as to their relevancy, the 5 and 95 percent confidence lines corresponding to a white spectrum* are indicated on these diagrams. From a statistical viewpoint alone, in spite of the fact that there are values which exceed these limits, their number does not exceed what one would have to expect for the number of spectral lines shown here. There are 30 spectral lines to the individual season. In 5 years, i.e., five winter seasons, one would expect 5 percent of the 150 spectral lines or about 8 cases before one could consider particular periods as significant. In other words, about 8 significant peaks

*A "white spectrum" is a random spectrum, in which the expected value of the power in each harmonic is the same.

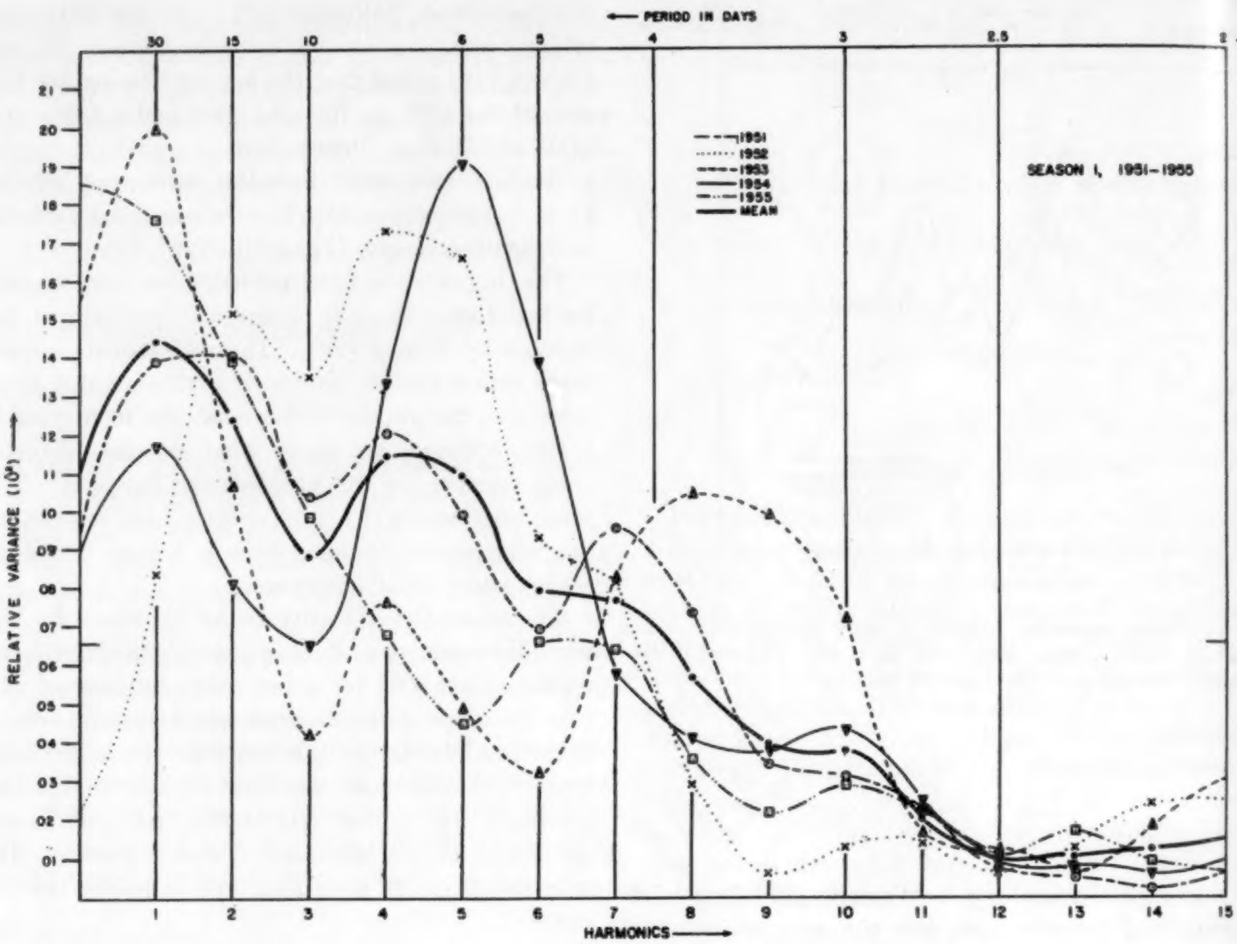

FIGURE 2.—Power spectrum analysis of daily average temperature data (°F.), Woodstock College, Md., for Season 1 (Jan. 1–Feb 15) 1951–55. Maximum lag is 30. The abscissa values at the base of the chart are linear in terms of harmonics; those at the top are in days. The average spectral (white) value is shown by the horizontal tick marks at 0.066. The heavy solid line connects the tips of the individually averaged spectral lines. All spectra are smoothed by the Hamming procedure.

could occur by chance. No season exhibits even that many significant spectral lines. Also, with respect to consecutive seasons through the years there is an insufficient number of significant spectral lines. For example, if the period of 10 to 15 days is selected, out of 200 spectral lines about 10 can be expected to show significance by chance. In our case we count actually 9. In the 2.5- to 3.5-day period 8 would be expected by chance, however, none shows up; yet there is a tendency for peaks at these periods in many of the single seasonal spectra. Similar conditions prevail with respect to other periods. Nor do the minima show statistical significance.

It might, nevertheless, be worthwhile to linger a little yet in the discussion of these data. They show definitely that in almost all seasons considerable power resides in relatively long periods. There is no tendency, however, for the spectra in these 5 years to show any particular preferences for certain periods by seasons. If one can attribute any meaning to these patterns it is that most of the seasons had their own characteristic "signature". It is premature to say whether such spectra could be used as circulation labels for the season. The only startling case of similarity of pattern is for the high winters (season 1) of 1954 and 1955. These were not particularly similar in their characteristics but both had rather well-marked 4-trough systems for most of the season over the higher latitudes of the Northern Hemisphere. This could explain the high power in the 5- to 6-day rhythm.

Perhaps another noteworthy element is the relative similarity shown for the seasons 3–1952, 8–1952, 1–1953, 2–1953, 6–1953, 7–1953, 2–1955 and 3–1955. All of these show their main power in the 10- to 15-day spectral band with a monotonous decline to both the longer and shorter periods. These may be related to the so-called index cycles. Takahashi and collaborators [33] referred to standing waves in their harmonic analysis of the 500-mb. heights in the Northern Hemisphere. However, their intervals were much longer than those noted here. But oscillations of the general circulation, as already noted in the introduction, can be derived even from elementary

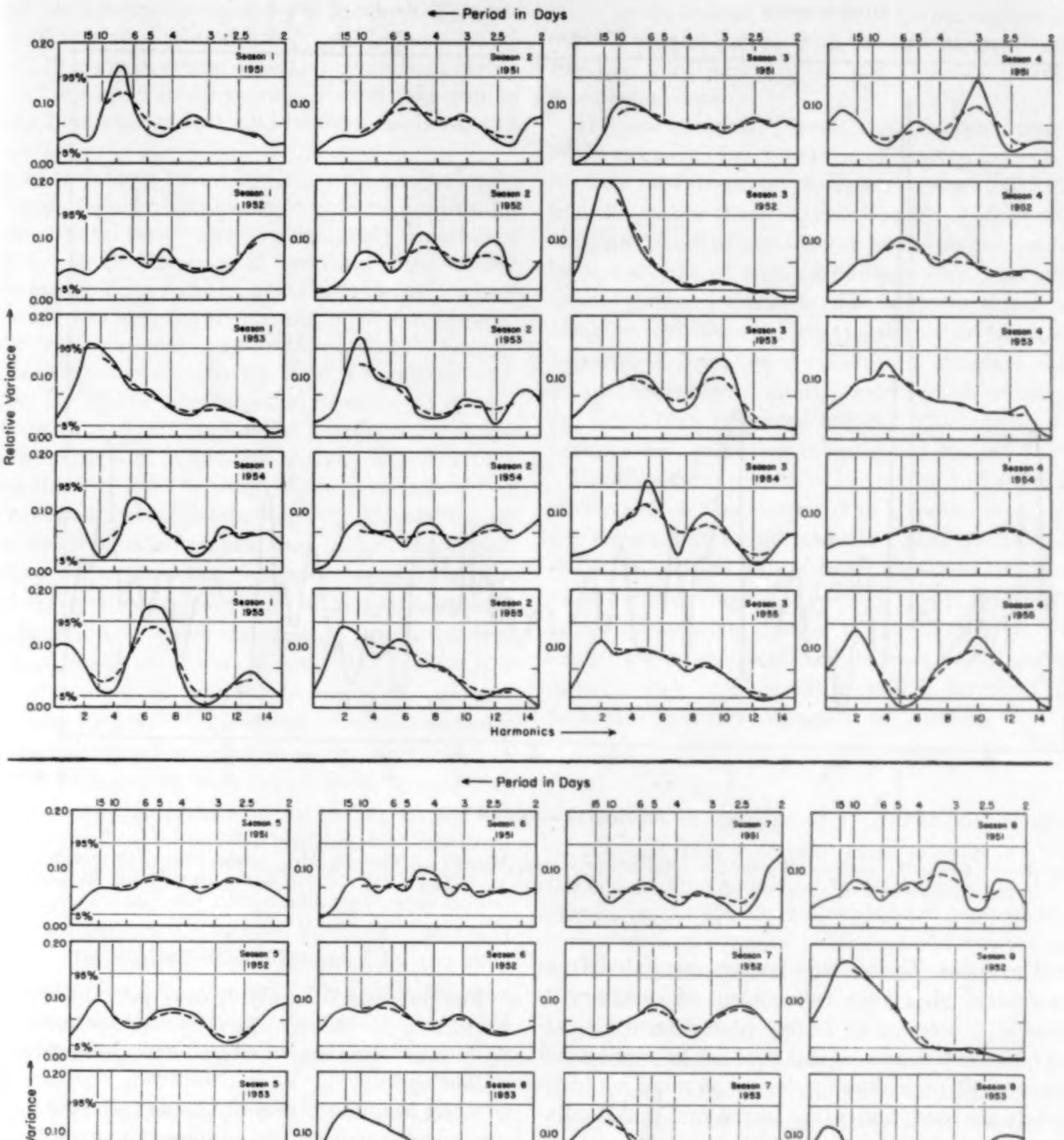

FIGURE 3.—Power spectrum analysis of Woodstock College daily precipitation data by 6-week seasons, January 1, 1951, through December 31, 1955. The abscissa values at the base of the chart are linear in terms of harmonics; those at the top in days. The χ^2 5 and 95 percent levels of significance relative to a white spectrum are shown. The average spectral (white) value is shown by the horizontal tick marks at 0.066. The solid line was produced by the Hamming smoothing procedures of the line power. The dashed lines are a binomial smoothing to the 4th power.

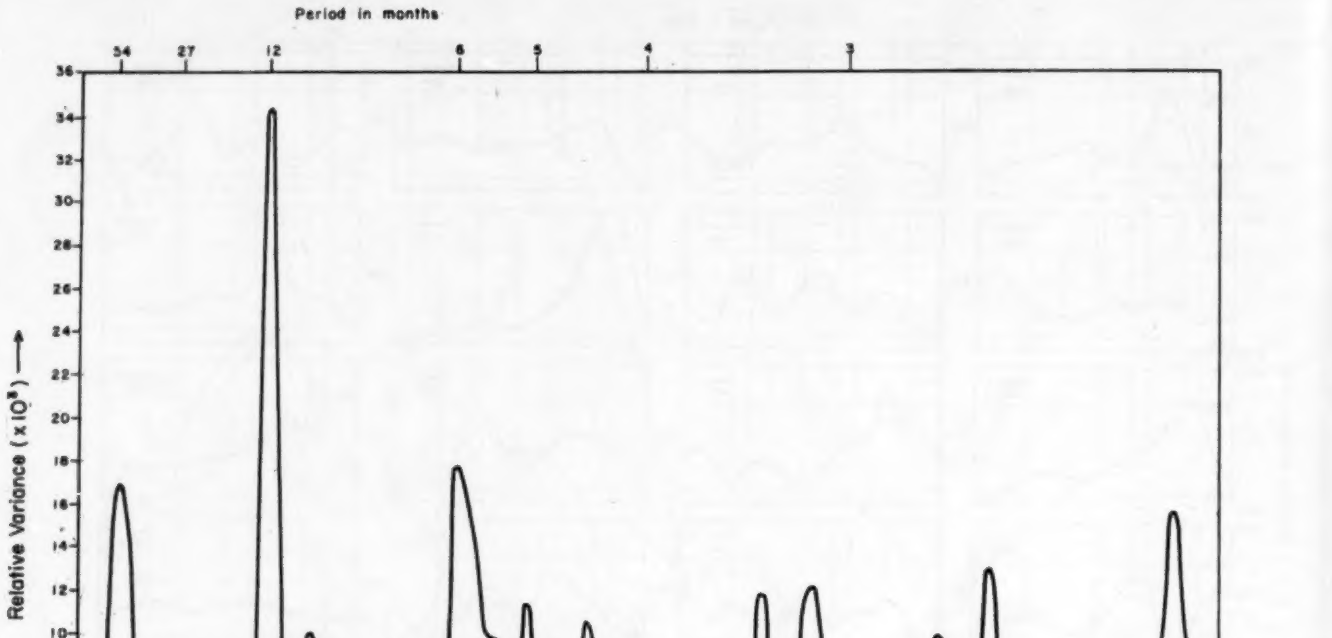

FIGURE 4.—Power spectrum analysis of monthly total precipitation, Woodstock College, Md., 1895–1956. 743 months, maximum lag 132, transformed by equation (1). The sum of the 132 smoothed relative variances equals 1 or 100 percent.

theoretical models. The absolute values calculated from these presently give only an order of magnitude. Smagorinsky [31] found an 11-day period from his calculations. The importance of this does not lie in the exact value, which will undoubtedly change as more sophisticated models are used, but rather in the fact that oscillatory elements result from theoretical approaches of the same order of magnitude as those noted here from the empirical end. This suggests that this avenue of approach, while presently barren of practical results, should not yet be considered as quite closed. It is, of course, obvious that a single-station analysis of a most variable element, such as precipitation, permits only a very limited outlook on these broad-scale phenomena in the atmosphere. To the man in the street the variation of precipitation and its rhythmical tendencies might be of paramount importance. He may be concerned if his favorite outdoor sport is rained out two or more weekends in succession. For the meteorologist, however, other indices are likely to be much better suited and more general in nature for spectral analysis.

LONG-PERIOD VARIATIONS

For purposes of studying long-period (low frequency) variations in climatological series, optimum techniques of power spectrum analysis are characterized by the following:

1. At least in the case of temperature, the monthly data are advantageously pre-whitened* to remove the annual cycle, whose large contribution to the total variance of such data may otherwise impair the ability of the analysis to resolve details at the other frequencies in which our interest primarily lies.

2. Large maximum lags must be used to resolve adequately fluctuations of very low frequency. Moderately small maximum lags ($\leqq 100$ months) may be justified if we anticipate the *population* spectra to be quite monotonous at the low-frequency end. Recalling the discussion in section 1, however, we may be no less justified in anticipating an irregular power distribution in the population spectra, of which the calculated spectra are small samples.

*See for example, Blackman and Tukey [8] for a discussion of the meaning of pre-whitening.

Therefore, spectral analysis involving a maximum lag of 546 months (45.5 years) was employed in which the resolution is sufficient to distinguish between fluctuations of the order of 10 years in period (the 11-year sunspot cycle) and those of the order of 30 years in period (the double sunspot and Brückner cycles), and between the latter and secular trend.

The use of such large maximum lags with a record only 86 years long, however, introduces very large amplitudes of spurious spectral power at a few randomly distributed wavelengths. In this manner, it complicates the testing of amplitude significance in the usual circumstance where certain *specific* wavelengths are not anticipated in advance to be significant by a priori physical hypothesis. That is, assuming a 95 percent significance level, a spectrum with a maximum lag of 546 months would be expected to contain between 17 and 37 "significant" peaks even if the spectrum were that of a random series. The use of a higher significance level to avoid Type I errors of this kind obviously increases the probability of overlooking physically real fluctuations which may in fact be present.

Precipitation spectra.—In this section, we shall be concerned primarily with the 546-month maximum lag analysis of precipitation, in which the seasonal march was first removed from the data. First, however, let us refer to a 132-month maximum lag analysis in which the seasonal march has been retained. This spectrum, shown as figure 4, applies to monthly precipitation totals at Woodstock from 1895 to 1956, which were transformed by equation (1) [14] which approximately normalizes an incomplete gamma-distributed variable (X) such as monthly total precipitation (Thom [34]). The annual cycle appearing in this spectrum is the most prominent feature of it, and accounts for 3.4 percent of the total variance of monthly precipitation. Its amplitude can be tested by the sampling theory of Tukey [35]. According to Tukey, the ratio of any spectral ordinate to the local ordinate of the *smooth* spectrum (here assumed equal to 1/132, the reciprocal of the maximum lag) is distributed as chi-squared/degrees of freedom. The degrees of freedom in turn are given by

$$\text{d.f.} = (2N - m/2)/m, \tag{12}$$

where N is the total record length, and m is the maximum lag used. In this case, $N=743$ months, $m=132$ months, and the degrees of freedom associated with a spectral peak involving k harmonics is $10.8k$. For the annual cycle, $k=1$, and the 99.9 percent confidence limit of the spectral amplitude (relative variance) is 0.022. The relative variance actually associated with the annual cycle is 0.034, which is thus highly significant.

Two other power maxima in this spectrum are also worth comment. The peak near a period of 6 months, while considerably less pronounced than that of the annual period, is significant at the 99 percent confidence level. Its physical reality is hardly to be doubted, inasmuch as the second harmonic of the annual period is frequently required along with the first harmonic to account for the total variance of the seasonal march in climatological data.

The nearly equally pronounced maximum near a period of 53 months (4–5 years) is of unique interest because, if real, its interpretation must be essentially "meteorological" rather than "astronomical." This spectral peak falls just short of significance at the 99 percent level. At least one peak of such magnitude should be expected to occur by chance somewhere in a spectrum containing as many as 132 harmonics. On the other hand, it should be recalled from the discussion in section 1 that quasi-cyclical variation of climate with periods of several years has often been suspected before. The nature of this apparent cycle is further investigated below.

Monthly total precipitation in the full 87-year record at Woodstock was subjected to a spectrum analysis with a maximum lag of 546 months. This spectrum is shown in figure 5 by the lighter line. The heavier line was produced by drawing a line through points obtained by averaging consecutive groups of 10 harmonics. For this analysis, the precipitation data were first transformed by equation (1), and then expressed in terms of departure from their monthly average by the relation

$$Z = Y - \overline{Y} + \overline{\overline{Y}} \tag{13}$$

where $\overline{Y}$ is the average of Y in that particular calendar month, and $\overline{\overline{Y}}$ is the grand average of Y in all calendar months. By this means, the variance due to the seasonal march, i.e., to all six resolvable harmonics of the annual cycle, has been completely eliminated from the spectrum; only the meteorological fluctuations remain.

The large resolution of this spectrum enables an examination of the single and double sunspot cycles, the Brückner cycle, and the higher harmonics of the double sunspot cycle which Abbot [1] claims to be useful in long-range forecasting. The extreme irregularity of the spectrum cannot, of course, be taken to mean that the true population spectrum of monthly precipitation—however we may care to define it—is comparably irregular. As with all work in spectrum analysis, an attempt is made to obtain an estimate of the true power spectrum of an infinitely long record from a finite portion of this record. This particular part of the record being analyzed may be considered as one of infinitely many pieces of record of similar length which could be obtained. The power spectrum constructed from a sample piece of record is subject to sampling variation within the period. Also the spectrum obtained may be considered in total as being a sample of the true spectrum. This means that a more definitive answer would be obtained by examining a sequence or series

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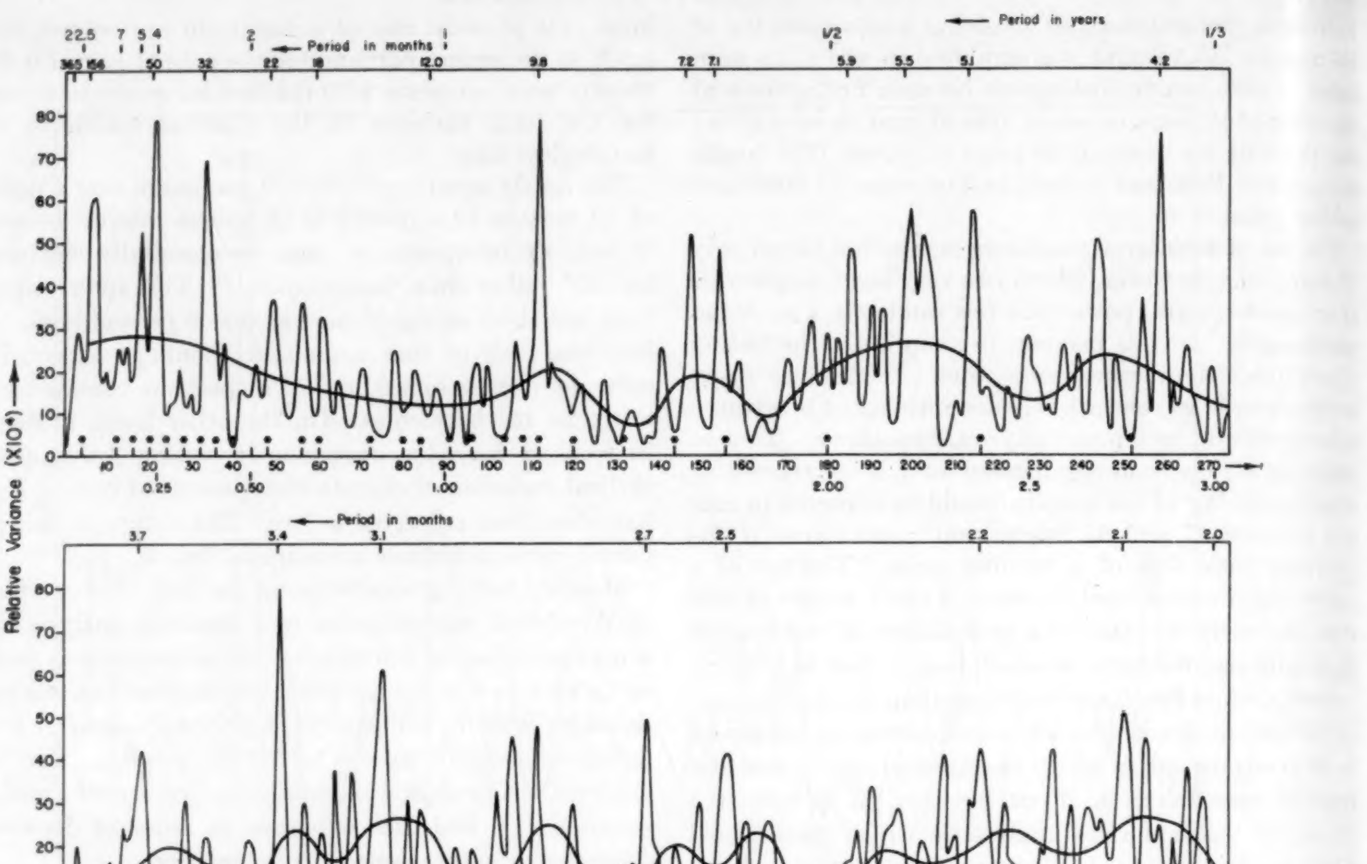

FIGURE 5.—Residual normalized power spectrum analysis of monthly total precipitation, Woodstock College, Md., 1044 months, 1870-1956. Maximum lag 546. Data values were transformed by equation (1) and modified by equation (13). The thin line connects the tips of the Hamming-smoothed line powers. The sum of the 546 line powers equals 1 or 100 percent. The heavy line connects the averaged line powers for each consecutive group of ten. The average spectral (white) is 1.000/546 or 18.31×10^{-4}. The 5 and 95 percent bounds for this average are 2.4×10^{-4} and 45.8×10^{-4}. Highest harmonics are probably inflated somewhat by aliasing. "Stars" mark periodicities after Abbot.

of spectra of finite and equal records. In this particular spectrum, only 3.3 degrees of freedom are associated with a power peak contributed by one harmonic. The critical ordinate magnitudes in figure 5 which may be assigned various levels of significance, assuming the null hypothesis of a white (rectangular) spectrum, are listed in table 1. Inspection of the data plotted in figure 5 reveals that the number of harmonics formally assigned significance on this basis is not itself significantly different from the number of harmonics expected to reach each significance level by chance if the precipitation series were actually random.

The power maximum in figure 4 which lies between 4 and 5 years is resolved in figure 5 into a principal maximum between 4.1 and 4.4 years (harmonics 21 and 22), and a secondary maximum between 4.7 and 5.2 years (harmonics 18 and 19). In relation to the null hypothesis of white noise, these peaks are significant at the 99.9 percent and 95 percent levels, respectively. A third maximum between 12.1 and 16.6 years (harmonics 6 and 7) also appears, which is significant at the 99 percent level according to the same null hypothesis.

In place of assuming white noise as in table 1, suppose we stipulate that the population spectrum is best repre-

TABLE 1.—*Significance of peaks in 546-month maximum lag spectra (figs. 5 and 7) based on Tukey's sampling theory with null hypothesis that population spectrum is that of white noise*

Number of harmonics contributing to peak, and degrees of freedom	Significance level (percent)		
	95	99	99.9
1 3.3 d.f.	0.00467	0.00669	0.00950
2 6.6	.00370	.00496	.00652
3 9.9	.00336	.00427	.00544
4 13.2	.00316	.00387	.00490

Mean variance of white spectrum=1/546=0.00183

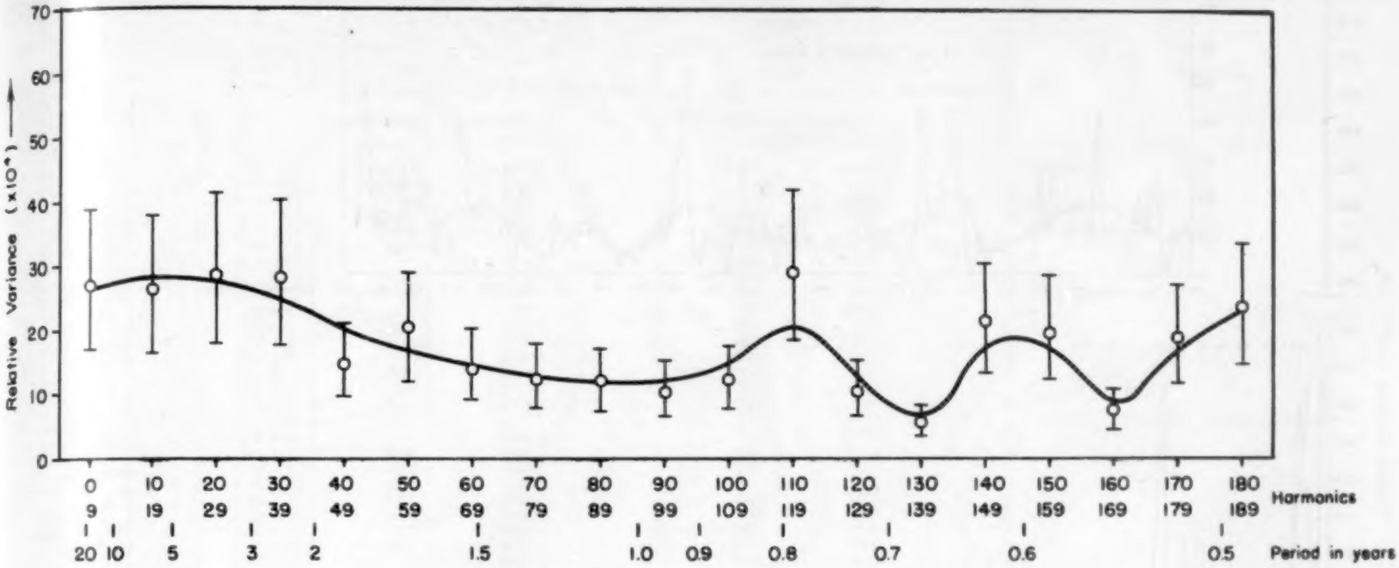

FIGURE 6.—Residual normalized power spectrum analysis of monthly total precipitation, Woodstock College, Md., 1044 months, 1870–1956. The harmonics have been averaged by consecutive groups of ten from figure 5. Averages are shown by circles and the 5 and 95 percent χ^2 limits by the extent of the vertical lines.

sented by the broad, modestly inflated power maximum involving the lowest 40 harmonics, which appears in figure 6. As indicated above, averages for consecutive groups of 10 harmonics were plotted and a line drawn through them to produce the heavier curve of figure 5. These same averages are indicated in figure 6 by the circles. Chi-squared limits of 5 and 95 percent are indicated by the horizontal tick marks on the ends of the vertical lines drawn through the circles. The heavier line of figure 6 has been produced by establishing 30 and 70 percent chi-squared limits and then drawing the curve subjectively with these limits as a guide. In such a case, only the two sharp peaks at harmonics 21 and 22 and harmonics 6 and 7 are significant at the 95 percent level, which is not impressive. Hence, one may interpret the precipitation spectrum in one of two ways: either the population spectrum at these long wavelengths is irregular with certain rather narrow peaks, or the population spectrum is rather modestly inflated in the entire interval between the zeroth and, say the 40th harmonics. With the present lack of corroborating evidence to suggest the reality of narrow bands of spectral power in this region of the spectrum, the writers tentatively prefer to consider the population as given by the smooth curves in figures 5 and 6, in which case *none* of the sharp spectral peaks corresponding to periods longer than 2 years is probably significant per se.

Temperature spectrum.—The 546-month maximum lag analysis of monthly mean temperature at Woodstock in the period 1870–1956 is shown as figure 7. In preparing this spectrum, equation (3) was first applied to the data in order to remove the seasonal march, described by the harmonics of the annual cycle. This had the effect of reducing the total variance from 240 $(°F.)^2$ to 11 $(°F.)^2$ and shows that 95 percent of the variance is accounted for by the seasonal march.

It will be noticed immediately that the first few harmonics are remarkably inflated in magnitude. Recalling that the observed temperatures between 1901 and 1914 were significantly biased (see section 2), one could anticipate that those particular harmonics would be inflated to some extent. Since the magnitude of the slippage of mean temperature could be rather confidently determined, it is possible to estimate the effect of the data inhomogeneity on the spectrum. One approach is to apply the Fourier integral theorem to the function illustrated in figure 8, which corresponds to the shape of the inhomogeneity in the Woodstock data. This leads directly to an expression for the amplitude of the sine and cosine components of the function, whose fundamental period is 2π.

Since the power contributed to the spectrum by a given harmonic is equal to half the square of the amplitude of that harmonic, the spectral power in the ith harmonic (whose period is $2\pi/i$) is found to be

$$A_i^2=\frac{.292}{i^2}[1-\cos(.3i\pi)],\ i=1,2,\ldots \qquad (14)$$

where A_i^2 is in $(°F.)^2$. Expressing this as a fraction of the total variance of monthly mean temperature at Woodstock, taken as $11(°F.)^2$, and suitably relating the fundamental periods of the function and the data

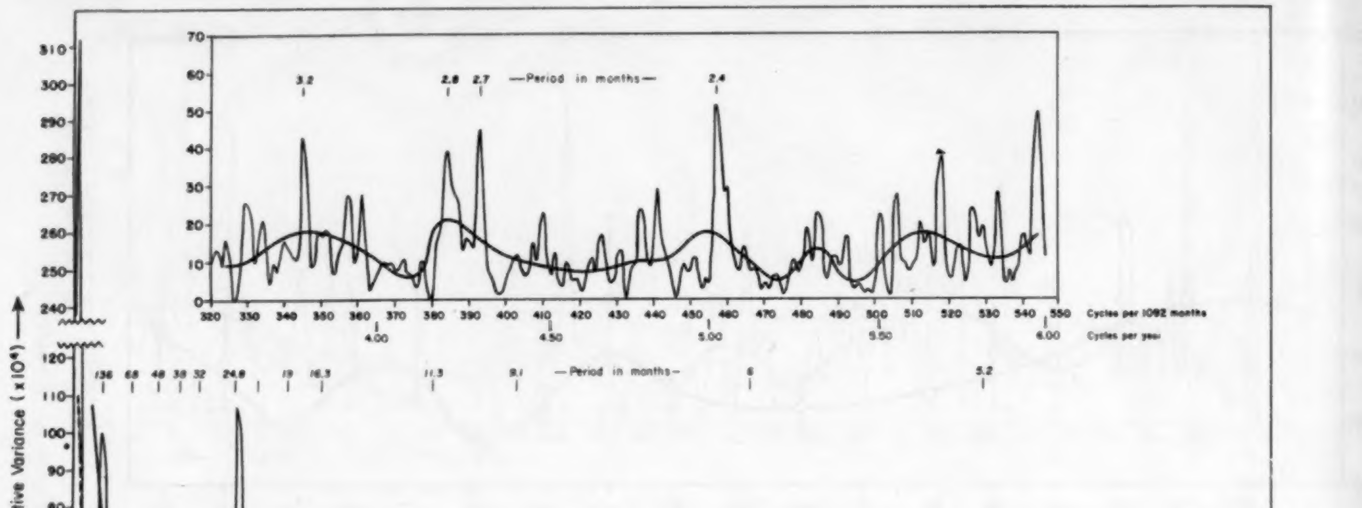

FIGURE 7.—Residual normalized spectrum analysis of monthly average temperature, Woodstock College, Md., 1032 months, 1870–1956. Maximum lag 546. Monthly means were extracted from data prior to analysis. The sum of the 546 ordinates equals 1.0. The thin line is the Hamming-smoothed line spectra. The heavy line connects the averaged line powers for each consecutive group of ten. The average spectra (white) is 1.000/546 or 18.31×10^{-4}. The 5 and 95 percent bounds for this average are 2.4×10^{-4} and 45.8×10^{-4}. The dashed curve is the contribution to variance by the temperature inhomogeneity of 1910–14. Highest harmonics are probably inflated somewhat by aliasing. "Stars" mark periodicities after Abbot.

series itself, one can estimate the relative uncertainty of the normalized spectrum in figure 7 introduced by the data inhomogeneity. The spectrum due to the inhomogeneity alone has been indicated in figure 7, and may be considered as the approximate *maximum* error at corresponding frequencies of the main spectrum which possibly has been caused by the inhomogeneity.

The significance of the peaks in figure 7, stipulating a null hypothesis of white noise, can be estimated by the aid of table 1. Details of the spectrum in the region of the first 25 harmonics, corresponding to all wavelengths longer than about 3.6 years, are shown in table 2. Even after the most pessimistic allowance for the inhomogeneity in the data, one sees that the amplitude of fluctuations longer than a half-century in period is highly significant. Although the Brückner cycle and the double (22-year) sunspot cycle are missing, considerable power is present in harmonics 6 through 9, corresponding to periods between 9.6 and 16.6 years. The harmonic which contains the single (11-year) sunspot cycle achieves significance at the 99.9 percent level. A lesser peak is found in harmonics 15 and 16, the latter of which contains the second harmonic of the 11-year sunspot cycle, believed by some authors to have physical importance [4]. The significance of harmonic 16 is 95 percent, while that of harmonics 15 and 16 jointly is 99 percent.

Another very prominent peak in the spectrum of figure 7 is found for harmonics 44 and 45, corresponding to periods of 24.0 to 25.1 months. The power in each of these harmonics is significant at the 99.9 percent level, again assuming the null hypothesis of the white spectrum. No physical interpretation of the sharp spectral peak near 25 months suggests itself.

As in the case of the precipitation spectrum, the null hypothesis of white noise, which was assumed in ascribing significance levels for these sharp spectral peaks of temperature, can be challenged as unrealistic. A different null hypothesis can be justified by averaging the power in

TABLE 2.—*Details of first 25 harmonics of 546-month maximum lag spectra of temperature and precipitation (figs. 5 and 7)*

Harmonic number	Inclusive period (years)	TEMPERATURE			PRECIPITATION			Remarks
		Power [1]		Significance [3]	Power		Significance [3]	
		Unsmoothed	Smoothed [2]		Unsmoothed	Smoothed [2]		
0	182–∞	−0.0026	(0.0182)	**	0.0000	0.0002		Secular trend.
1	60.8–182	(.0438)	(.0214)	**	.0005	.0008		
2	36.4–60.8	(.0003)	(.0099)	**	.0022	.0020		
3	26.0–36.4	(−.0050)	(−.0009)		.0029	.0028		Brückner cycle.
4	20.2–26.0	(.0061)	(−.0014)		.0033	.0023		Double sunspot cycle.
5	16.6–20.2	(−.0018)	(.0042)		−.0007	.0022		
6	14.0–16.6	(.0146)	(.0075)	*	.0081	.0058	†	
7	12.1–14.0	.0023	.0075	*	.0066	.0060	†	
8	10.7–12.1	.0123	.0099	**	.0026	.0031		Single sunspot cycle.
9	9.6–10.7	.0119	.0084	*	.0008	.0018		
10	8.7–9.6	.0039	.0016		.0031	.0020		
11	7.9–8.7	.0041	.0024		.0004	.0016		
12	7.3–7.9	.0045	.0038		.0026	.0022		
13	6.7–7.3	.0018	.0030		.0030	.0025		
14	6.3–6.7	.0044	.0037		.0011	.0021		
15	5.9–6.3	.0041	.0051	†	.0036	.0025		
16	5.5–5.9	.0081	.0055	†	.0014	.0017		Second harmonic of single sunspot cycle.
17	5.2–5.5	.0006	.0024		.0007	.0023		
18	4.0–5.2	.0006	.0004		.0070	.0053	†	
19	4.66–4.9	−.0002	.0000		.0059	.0042		
20	4.44–4.66	.0001	.0001		−.0028	.0024		
21	4.24–4.44	.0006	.0004		.0113	.0076	*	
22	4.05–4.24	.0005	.0021		.0093	.0079	*	
23	3.87–4.05	.0072	.0039		.0012	.0029		
24	3.71–3.87	−.0004	.0016		.0002	.0009		
25	3.57–3.71	.0007	.0004		.0022	.0012		

1 Temperature values in parentheses have been whitened to maximum extent permitted by data inhomogeneity.
2 Smoothing by Hamming formula (see text, section 3).
3 Null hypothesis corresponds to white noise. †=significance at 95 percent; * at 99 percent; ** at 99.9 percent level.

successive blocks of 10 harmonics each, and fitting a curve to these averages which is as smooth as their fiducial limits of amplitude permit. Such curves for both the temperature and precipitation spectra are shown in figures 6 and 9. The fiducial limits shown are 5 and 95 percent limits, which could be readily calculated by adding the degrees of freedom associated with each harmonic involved in the averages. It will be noticed that the smooth curves in figures 6 and 9 are *not* consistent with the assumption of white (rectangular) population spectra, but that the inconsistency is serious only in the case of temperature. If the temperature curve in figure 9 is then used as the null hypothesis for testing the sharp spectral peaks discussed above, one finds, for example, that the sharp peak at harmonics 44 and 45 (periods near 25 months) is significant at the 99 percent level only, which, although noteworthy, is not overly impressive in a spectrum of such fine resolution and in the absence of an a priori reason for expecting to find power at that precise wavelength. But now the broad spectral maximum in the smoothed spectrum of figure 9 near this same period of 25 months must be recognized as being highly significant in its own right. This significance evidently surpasses the 99.99 percent level. The maximum accounts for roughly one quarter of the variance of *annual* mean temperatures.

With this revised null hypothesis of the temperature spectrum, the sharp spectral peak corresponding to the 11-year sunspot cycle loses significance even at the 95 percent level. This conclusion is readily vitiated, however, by slight changes in the exact form of the fitted curve in figure 9. The second harmonic of the solar cycle (about 5.6 years in period) also loses significance at the 95 percent level under this revised null hypothesis.

A further use of both the temperature and precipitation spectra is that of verifying Abbot's [1] hypothesis to the effect that selected harmonics of the double sunspot cycle can be used as the basis of long-range weather prediction.

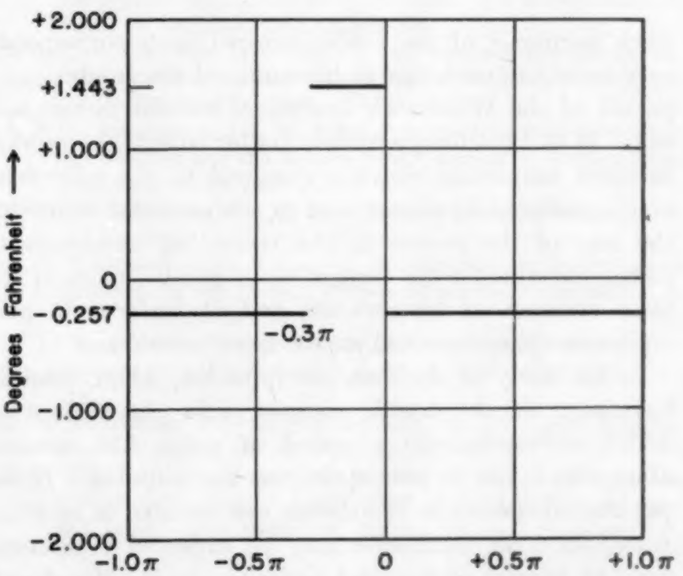

FIGURE 8.—Function resembling data inhomogeneity of monthly average temperature at Woodstock College, Md., in period 1870–1956.

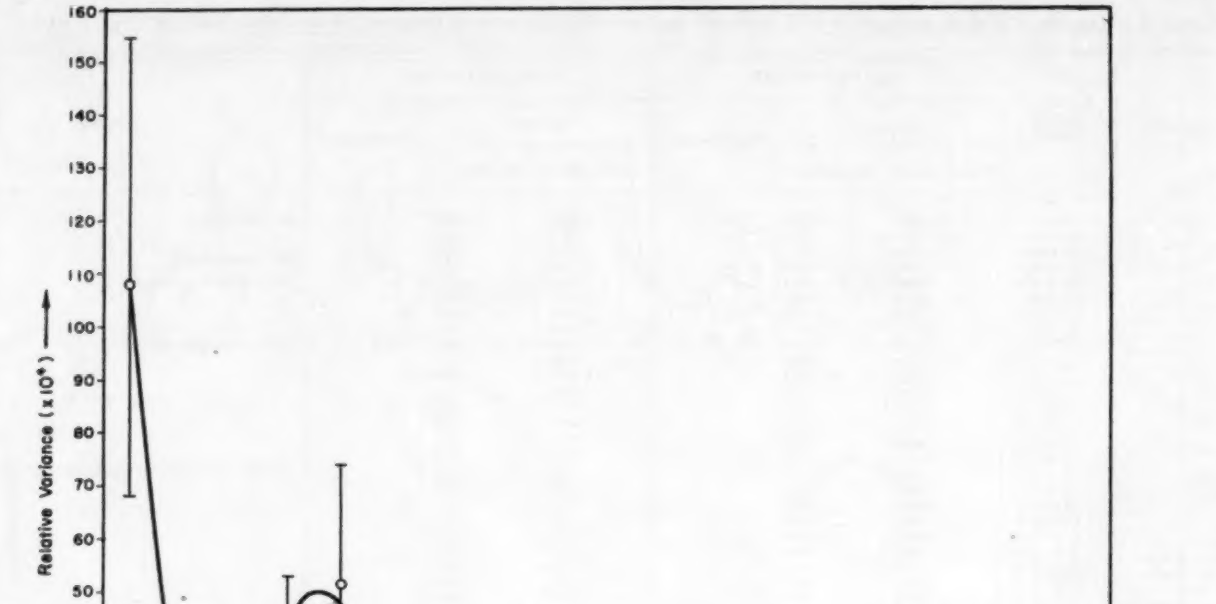

FIGURE 9.—Residual normalized power spectrum analyses of monthly average temperature, Woodstock College, Md., 1032 months, 1870-1956. The harmonics were averaged by consecutive groups of ten from figure 7. Averages are shown by the circles, the 5 and 95 percent χ^2 limits by the extent of the vertical lines.

Each harmonic of the double sunspot cycle corresponds very nearly to each *fourth* harmonic of the fundamental period of the Woodstock analyses discussed in this section. It is, therefore, a simple matter to sum the powers in those harmonics which correspond to the *solar* harmonics selected by Abbot, and to compare this sum with the sum of the powers in the remaining harmonics to determine whether the former can "explain" more of the total variance of temperature and (transformed) precipitation than one could expect from coincidence.

In his study of Arizona precipitation, Abbot used 28 harmonics of the double sunspot cycle, the highest of which corresponds to a period of about 4.34 months. Harmonic 2, the 11-year cycle, was not included. If the population spectra at Woodstock are assumed to be white noise, these 28 harmonics may be expected to account for 5.13 percent of the total variance. In the Woodstock precipitation spectrum, they actually account for 4.97 percent of the total, which is not significantly different from 5.13 percent. In the temperature spectrum, the 28 harmonics account for 7.36 percent of the total, which is significantly different from 5.13 percent at the 99 percent level according to the chi-square test with 92 available degress of freedom. Since, however, we have had to conclude that the population temperature spectrum cannot in fact be white, we have to take a second look at this last conclusion. Assuming the population spectrum to be the temperature curve in figure 9, we find that Abbot's selected harmonics should be expected to contribute about 7.45 percent of the total variance instead of the 5.13 percent applying to a rectangular spectrum. This compares closely with the 7.36 percent total actually contributed by the selected harmonics. Because the smooth spectrum in figure 9 does not itself exhibit singular power at harmonics corresponding to the solar harmonics, we can safely conclude that no evidence can be found in the Woodstock data to support Abbot's hypothesis. As variations of temperature and precipitation are highly correlated over large geographical areas, this strongly implies that Abbot's method of prediction as applied to any part of

the eastern central United States would show negligible skill over extended periods of time.

Conclusions concerning long-period variations.—The results of the power spectrum analyses of the Woodstock data lead us to the following conclusions, with respect to long-period variations:

1. The spectrum of temperature reveals, in part, two highly significant maxima of variance, one with periods between about 1.8 and 2.7 years, and the other with periods longer than about 50 years.

2. The spectrum of precipitation reveals only minor departures from randomness, the most notable of which consists of a modest inflation of variance in periods longer than about 2 years.

3. The 11-year sunspot cycle is suggested in the temperature spectrum, but not in the precipitation spectrum. Its level of significance in the former is 99.9 percent under the null hypothesis of a white spectrum, but somewhat less than 95 percent under the null hypothesis corresponding to the smooth spectrum shown in figure 9. Its contribution to the total variance of *annual* mean temperatures is about 3 percent.

4. The double (22-year) sunspot cycle is absent from both the temperature and precipitation spectra.

5. The Brückner cycle, of the order of 35 years in period, is virtually absent from both the temperature and precipitation spectra.

6. The second harmonic of the solar cycle, about 5.6 years in period, occurs in the temperature spectrum with a significance of 95 percent under the null hypothesis of a white spectrum, but with a lesser significance under the null hypothesis corresponding to the smooth spectrum in figure 9.

7. In the case of both the precipitation and temperature spectra, major contributions to the total variance of monthly data derive from all portions of the spectra. There are no important gaps in either spectra except in a relative sense, as, for example, the relative minimum in the temperature spectrum near a period of 4 years.

8. The harmonics of the double sunspot cycle, used by Abbot in his scheme of long-range prediction, do not contribute more to the total variance of either temperature or precipitation at Woodstock than the amount ascribable to chance.

ACKNOWLEDGMENTS

The authors are much indebted to Professor Hans Panofsky, of Pennsylvania State University, for helpful discussions on the procedures employed in this paper. At the National Weather Records Center, Mr. James Roddy ran the electronic computer analysis work and Mr. Ray Crane did the drafting work for us. We are grateful to both.

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MEAN UPPER-AIR DATA FOR SELECTED WORLD STATIONS

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ABSTRACT

Mean upper-air pressure heights, temperatures, and mixing ratios are presented for 48 radiosonde stations well distributed in longitude around the globe. Of the 48 stations whose means are given, a majority were selected from arid zones, equatorial regions, and from the Southern Hemisphere. This geographical distribution, plus the fact that humidity means are given, constitute the chief value of the data presented.

In recent years several series of mean upper-air charts have been published that present temperature and pressure-height normals. None of these, to my knowledge, has included upper-air mixing ratio means, and also none extends across the equatorial zone into the Southern Hemisphere. Hence, in a current study that involved analysis of mean precipitable water amounts for stations representative of several different climatic regions well distributed around the globe, it became necessary to compute such upper-air means from original data tabulations. Until such time as really extensive tabulations of upper-air climatic data become available, these data should have reference value, so they are briefly summarized here (table 1).

No data for United States stations were computed, since an excellent tabulation has recently been published by Ratner [1]. Data for Mexican stations were taken from individual issues of two U.S. Weather Bureau publications, *Monthly Weather Review* and *Climatological Data National Summary.* All other data have been extracted from *Monthly Climatic Data for the World*, a U.S. Weather Bureau compilation. A total of 48 stations was considered.

It is important to note that the original observations were made with a wide variety of aerological sounding equipment and under a variety of levels of control. Furthermore these published data have not been subjected to any quality control by the publishing agency. Hence, the means here presented must be recognized as being rather uneven in quality. Nevertheless they should be useful as provisional means for areas of the world for which almost no published averages are currently available.

Mean conditions at three standard pressure surfaces (850, 700, 500 mb.) and for the climatically extreme months of January and July were obtained. Heights (H) of the pressure surfaces in meters above sea level, temperatures (T) in degrees Celsius, and mixing ratios (X) in grams per kilogram were the quantities averaged. The last quantity was obtained from mean relative humidities or mean dew points (depending on the data source). Analysis showed that errors due to nonlinearity in the dependence of saturation mixing ratio upon temperature that are incurred by such a method of averaging are of the order of only a fraction of a percent. The number of calendar years of record varied, unavoidably, from station to station, with maximum lengths of 10 years. The longest records cover the period 1949–58, and all data fall somewhere within that decade. To indicate to the user of the tables the number of years of record for which each station's means have been calculated, I give under the heading "N" the number of years of record used in computing the mean 700-mb. data. (The latter level is uniformly used in order to avoid having to cite special cases where for station-altitude reasons there exist no 850-mb. data.)

The inevitable problem of missing humidity data at upper levels arises here, especially at the 500-mb. level. It has been handled as follows: If only one year had no humidity data reported for a given level and month, the omission was ignored in the sense that the mean was computed for just that series of years for which actual humidities were reported. If more than one humidity entry was missing, the mean temperature for the group of missing cases was determined, and the so-called "motorboating" mixing ratio based on U.S. Weather Bureau radiosonde experience was taken to correspond to the mean temperature for that group of cases. Then a weighted average of this motorboating value plus the mean of the actually reported humidities (converted to mixing ratios) was calculated and listed. It is clear that to use a U.S. Weather Bureau motorboating value for *foreign* stations' missing humidity data is far from satisfactory in view of differences in instrumental characteristics; but this procedure is still preferable to simple omis-

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TABLE 1.—*Mean upper-air data for selected world stations. H=height of pressure surface (meters, MSL); T=temperature (° C.); X=mixing ratio (gm./kg.); N=number of years record used in computing 700-mb. data*

Station	N	JANUARY									JULY								
		850 mb.			700 mb.			500 mb.			850 mb.			700 mb.			500 mb.		
		H	T	X	H	T	X	H	T	X	H	T	X	H	T	X	H	T	X
Jan Mayen Island	5	1286	−12.0	1.5	2750	−19.4	0.8	5176	−35.0	0.3	1418	1.3	4.1	2964	−5.2	2.5	5540	−20.2	0.9
Keflavik, Iceland	7	1261	−6.4	1.9	2748	−16.9	0.9	5199	−32.7	0.3	1401	2.7	2.9	2951	−5.3	2.8	5521	−20.3	0.8
Sodankyla, Finland	6	1289	−10.4	1.6	2760	−18.5	0.9	5194	−34.3	0.2	1440	6.7	5.1	3008	−1.9	3.2	5610	−17.0	1.1
Stockholm, Sweden	8	1368	−7.1	1.9	2858	−14.7	1.0	5326	−31.0	0.3	1457	6.8	5.1	3024	−2.0	3.1	5625	−17.4	1.1
Lerwick, Great Britain	8	1354	−4.2	2.5	2862	−12.2	1.0	5353	−28.8	0.3	1435	5.2	4.8	2995	−2.4	2.5	5596	−17.8	0.8
Casablanca, Morocco	3	1520	5.3	4.5	3056	−2.3	1.7	5671	−19.1	0.5	1550	21.1	5.5	3201	11.3	2.3	5901	−9.2	0.8
Ft. Trinquet, Morocco	6	1519	9.1	3.0	3112	−2.1	1.4	5756	−14.0	0.5	1534	27.4	5.7	3216	14.0	3.1	5934	−8.4	1.6
Algers, Algeria	9	1482	2.9	3.4	3031	−5.7	1.5	5589	−22.1	0.4	1537	21.0	5.4	3192	10.3	2.9	5888	−9.9	1.0
Colomb-Bechar, Algeria	9	1512	6.0	3.0	3070	−3.0	1.6	5630	−18.8	0.4	1543	28.8	5.5	3224	13.9	3.1	5942	−8.5	1.6
Aoulef, Algeria	8	1503	9.[illegible]	2.3	3092	1.4	1.2	5718	−14.7	0.5	1528	28.4	3.4	3207	13.8	2.6	5924	−7.8	1.2
Benina, Libya	8	1492	5.2	3.6	3057	−2.5	1.4	5640	−18.6	0.4	1528	19.7	3.6	3171	10.4	2.5	5874	−5.7	0.7
Tunis, Tunisia	4	1454	2.0	3.4	2998	−6.2	1.7	5573	−23.2	0.4	1556	19.3	6.4	3200	9.2	2.7	5866	−9.6	0.9
Cairo, Egypt	8	1506	5.9	3.4	3090	−1.3	2.2	5642	−16.6	0.6	1495	21.2	7.8	3153	12.6	3.8	5886	−3.4	1.4
Khartoum, Sudan	4	1506	18.4	4.4	3147	9.8	2.3	5848	−8.0	0.8	1506	22.4	10.9	3158	11.2	6.7	5870	−7.0	2.8
Dakar, Senegal	8	1506	18.2	3.8	3135	8.1	2.8	5690	−9.1	1.3	1517	19.0	10.1	3153	10.1	5.5	5844	−7.3	2.3
Niamey, French Nigeria	6	1514	18.0	2.7	3147	9.7	2.2	5850	−7.0	0.9	1525	20.1	10.2	3168	9.9	5.9	5873	−4.4	2.2
Lagos, Nigeria	3	1519	18.2	9.8	3150	9.1	5.3	5858	−5.9	1.6	1531	15.8	11.8	3161	8.3	7.2	5866	−6.5	2.7
Douala, Cameroons	3	1493	17.6	11.2	3132	8.6	4.0	5831	−5.7	0.8	1514	15.6	1.6	3146	7.8	6.1	5850	−6.5	2.1
Bangui, French Equatorial Africa	5	1496	20.5	8.2	3148	10.1	4.3	5859	−5.7	1.1	1511	18.1	11.5	3154	8.6	6.0	5860	−6.4	2.2
Nairobi, British East Africa	8				3160	9.7	6.2	5875	−5.6	1.6				3163	6.9	7.6	5868	−6.4	1.4
Ankara, Turkey	6	1463	−1.3	3.2	2979	−8.9	1.8	5515	−26.5	0.4	1489	16.9	7.2	3117	7.1	4.1	5801	−9.3	1.0
Habbaniya, Iraq	7	1493	4.3	3.2	3048	−4.4	1.4	5620	−21.8	0.4	1449	28.0	3.5	3138	14.2	2.3	5866	−2.6	0.6
Bahrein, Arabia	8	1515	9.6	3.9	3096	1.6	2.2	5739	−14.5	0.8	1440	29.5	5.0	3128	16.7	2.8	5867	−3.1	1.3
Aden, Arabia	8	1531	16.1	7.8	3168	9.5	3.2	5882	−6.1	0.7	1461	26.8	11.3	3136	14.4	6.4	5864	−7.0	2.6
Quetta, West Pakistan	4				3078	−1.4	4.1	5700	−17.4	(0.5)				3100	18.6	10.0	5873	−1.2	4.2
Karachi, West Pakistan	4	1508	12.8	5.7	3125	5.0	3.6	5788	−10.0	1.2	1422	23.5	14.2	3120	17.5	8.6	5866	1.0	2.9
New Delhi, India	10	1509	10.9	4.4	3100	0.8	2.8	5715	−16.7	(0.5)	1423	24.1	16.5	3085	13.2	11.0	5846	−1.3	5.6
Jodhpur, India	10	1514	11.4	4.1	3106	1.8	2.4	5678	−14.6	(0.6)	1425	23.4	15.4	3092	13.3	9.5	5842	−2.2	3.2
Nagpur, India	8	1519	16.3	6.1	3138	6.0	3.1	5824	−9.0	(0.9)	1434	21.4	15.0	3092	11.9	9.7	5839	−2.2	(1.4)
Trivandrum, India	9	1510	17.8	10.6	3151	10.2	4.8	5872	−5.3	(1.2)	1490	17.3	12.0	3130	9.7	7.6	5850	−5.5	(1.2)
Calcutta, India	10	1518	12.8	4.8	3122	5.1	2.2	5786	−10.8	(0.7)	1429	21.5	14.5	3089	12.7	9.7	5845	−1.5	4.7
Madras, India	8	1523	16.5	7.0	3158	10.3	2.8	5883	−5.1	(1.2)	1468	21.3	13.2	3122	10.4	8.8	5851	−4.2	(1.2)
Port Blair, Andaman Island	7	1517	17.1	10.3	3155	9.9	4.5	5873	−5.0	(1.2)	1488	18.9	12.6	3137	10.6	7.9	5860	−4.3	1.2
Cocos Island	4	1504	15.7	9.5	3142	8.3	4.4	5842	−6.6	1.4	1509	15.6	14.5	3142	8.8	5.1	5856	−5.7	1.7
Hong Kong	7	1545	10.2	6.4	3143	5.0	2.8	5786	−8.1	0.6	1474	18.9	14.3	3125	11.5	7.3	5862	−3.5	3.0
Wake Island	7	1528	14.0	8.2	3149	9.8	(2.7)	5868	−5.7	(1.2)	1536	17.2	11.1	3157	9.0	5.7	5880	−6.8	2.1
Canton Island	8	1479	17.7	10.5	3122	10.6	1.7	5849	−4.4	2.2	1492	17.6	10.3	3132	9.9	4.8	5851	−5.2	1.9
Darwin, Australia	8	1474	19.1	11.2	3116	9.4	6.2	5853	−5.2	2.9	1508	15.6	6.3	3137	9.6	2.8	5852	−5.9	1.5
Alice Springs, Australia	8	1514	23.4	5.4	3156	9.8	4.4	5860	−6.8	1.2	1538	7.7	3.3	3124	2.5	1.8	5775	−11.6	0.9
Cloncurry, Australia	9	1474	21.3	16.4	3111	9.1	6.3	5772	−4.6	2.1	1516	11.6	4.2	3121	5.8	2.5	5793	−8.3	1.3
Charleville, Australia	9	1494	19.7	7.1	3128	7.2	4.6	5815	−8.6	1.4	1521	6.9	3.2	3095	−0.1	1.7	5716	−15.2	0.8
Townsville, Australia	7	1481	17.7	10.5	3118	9.0	5.6	5833	−5.6	2.2	1520	11.5	6.2	3130	6.6	2.2	5818	−7.7	0.8
Macquarie Island	7	1290	−0.1	3.2	2838	−7.4	1.6	5357	−22.6	0.5	1340	−4.4	2.1	2839	−12.0	1.0	5329	−28.8	0.3
Mazatlan, Mexico	10	1518	16.3	4.9	3138	5.9	2.4	5808	−11.0	1.0	1515	20.0	12.7	3165	10.7	7.8	5884	−6.5	3.0
Cuidad Victoria, Mexico	6	1514	11.8	6.5	3248	5.4	3.6	5966	−11.6	1.0	1523	22.0	10.9	3167	9.0	6.1	5876	−6.5	2.0
Tacubaya, Mexico	10				3151	9.2	4.3	5835	−8.4	1.2				3157	10.1	8.5	5874	−6.7	3.4
Vera Cruz, Mexico	4	1538	14.0	7.5	3155	6.8	3.4	5849	−8.3	1.0	1524	18.5	11.1	3161	8.6	6.0	5870	−6.6	2.2
Merida, Mexico	10	1549	14.3	8.9	3170	7.5	3.3	5877	−8.3	1.0	1552	21.3	13.8	3190	8.0	6.1	5896	−6.9	2.5

sion of all cases of missing data since to compute an average on the basis of only *reported* humidities in records containing entries missing due to upper-air dryness or anomalous coldness will yield an erroneously high value. On the other hand, to treat missing cases as zeroes will almost always yield an underestimate, so the procedure used is the best available compromise. In all instances where this procedure has had to be used, the mean mixing ratio in question has been enclosed in parentheses. It will be seen that only a single 700-mb. mixing ratio out of a total of 96 cases depends on such a motorboating adjustment, but the 500-mb. data includes 12 such cases out of 96.

ACKNOWLEDGMENTS

The support of the Rockefeller Foundation in the climatological studies of which this work was one part is gratefully acknowledged. The computational and tabulation work was done with the assistance of Mrs. Nell Hansen and Mrs. Diane Davis.

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Weather Notes

SEVERE HAIL, SELDEN, KANSAS, JUNE 3, 1959

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[Manuscript received August 26, 1959]

On the afternoon of June 3, 1959, Selden, a small town in the northwestern corner of Sheridan County, Kansas, suffered one of the most severe hailstorms in the State's record. In contrast to most severe hailstorms, there was little wind and the stones were small. The tragedy was produced by the sustained fall of hailstones for approximately 85 minutes.

Late in the afternoon, about 5:15 p.m., the hail began and with the initial stones the wind was quite strong and quickly changed directions breaking many windows. The

FIGURE 1.—Aerial view showing 18 inches of hail covering Selden, Kans. on June 3, 1959. Outline of fields can be seen in distance, which shows the extent of the hail southwest of Selden. (Photo courtesy *Norton Daily Telegram*.)

FIGURE 2.—Aerial view of Selden and vicinity, June 3, 1959. Southern edge of hail area is shown at top of picture. (Photo courtesy *Norton Daily Telegram.*)

FIGURE 3.—Aerial close-up of Selden, June 3, 1959, shows how trees were stripped of leaves and flat roofs were caved in. Black area of building next to the quonset is collapsed part of roof. (Photo courtesy *Norton Daily Telegram.*)

wind soon quieted over the area but hail continued to fall incessantly until 6:40 p.m.

The area covered by the hail was elongated, about 9 miles northeast to southwest and 6 miles across at the widest. Selden was located a little to the northeast of the center of the area.

In addition, to the hail, rain was variously estimated at 3 to 5 inches, and many basements were flooded.

The hail accumulated to a depth of 18 inches and was mostly pea or marble size and many of the stones were soft. Drifts were 3 to 4 feet deep at the sides of buildings where it fell from the roofs. Piles along the streets and roads remained for 2 days. Traffic on U.S. Highway 83 was halted, and approximately 100 automobiles were stalled 4 hours, or more, until bulldozers could open the roads. Snow plows were unable to move the weight.

The Red Cross reported 2 business buildings destroyed, major damage done to 10 business houses, 8 farm buildings, and 5 homes. Minor damage was indicated to almost every building in the area, 154 homes, 125 farm buildings, and 27 business buildings. In some measure the damage was due to the continuous pelting of the stones but the greater losses resulted from the tremendous weight of accumulated hail on flat- or nearly flat-roofed buildings, causing them to collapse. The hail accumulation on a truck scale, 10 x 45 feet, weighed 28,000 pounds, or 62.2 pounds per square foot. Damage over the area was estimated at $500,000.

Trees were stripped of leaves and small branches, and with the ground hail-covered the town had much the appearance of winter. In just a few minutes the temperature on local thermometers dropped from near 80° to 38° during the storm.

There were several narrow escapes as roofs collapsed, especially in the restaurant, where a number of people had collected, but only one man was slightly injured when struck on the head as an awning gave way due to the weight of the hail. Two men caught in a pickup truck were unable to shout loud enough for the other to hear above the roar of the hail on the metal cab roof.

A local citizen described the storm as follows, "The hail began and just didn't stop."

A news writer expressed his reaction to the scene quite well in these words, "I saw a chunk of January in the heart of June."

WORLD RECORD ONE-MINUTE RAINFALL AT UNIONVILLE, MARYLAND

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and

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[Manuscript received October 14, 1958; revised August 10, 1959]

On July 4, 1956, 1.23 inches of rain apparently fell in one minute at Unionville, Md. During the afternoon intense thunderstorms prevailed in the Piedmont area over northern Virginia and adjacent portions of north central Maryland. Unusual instability and intense storm development was further evidenced by a report of a funnel cloud near Quantico, Va.

At a U.S. Geological Survey stream gaging station, Little Pipe Creek at Avondale, about 10 miles northwest of Unionville, Md., streamflow reached the greatest peak flow for this station since it was established in August 1947. Further, based on an analysis of the annual extreme peak discharges, the July 4, 1956 peak discharge is estimated to have a return period of more than 20 years. At Westminster, 12 miles northeast of Unionville, severe thunderstorms brought the heaviest rainstorm in years. Streets resembled rivers, and many basements were flooded with several inches of water. Telephone communications were put out of order by the heavy rains, and fields were badly eroded. Gardens were flooded with damage to vegetables, and the local hay crops were flattened in the fields.

Associated with this area of heavy storms was the cloudburst reported at Unionville, Md. during which 1.23 inches of precipitation occurred in an estimated period of 1 minute. The total precipitation in the Unionville storm was 3.60 inches for the period from 1450 EST to 2330 EST with a total of 2.84 inches occurring during the 50-minute period from 1450 to 1540 EST. Many basements in Unionville were flooded; at least one was filled to the ground level or higher. Residents reported only one severe bolt of lightning and one loud crash of thunder but little or no wind during the storm. The sky became so dark that residents had to switch on electric lights. Mr. G. P. Von Eiff, cooperative weather observer, was in Frederick, Md. at the time of the storm and reported that clouds in the direction of Unionville were intensely dark. The wife of the cooperative weather observer reported rainfall

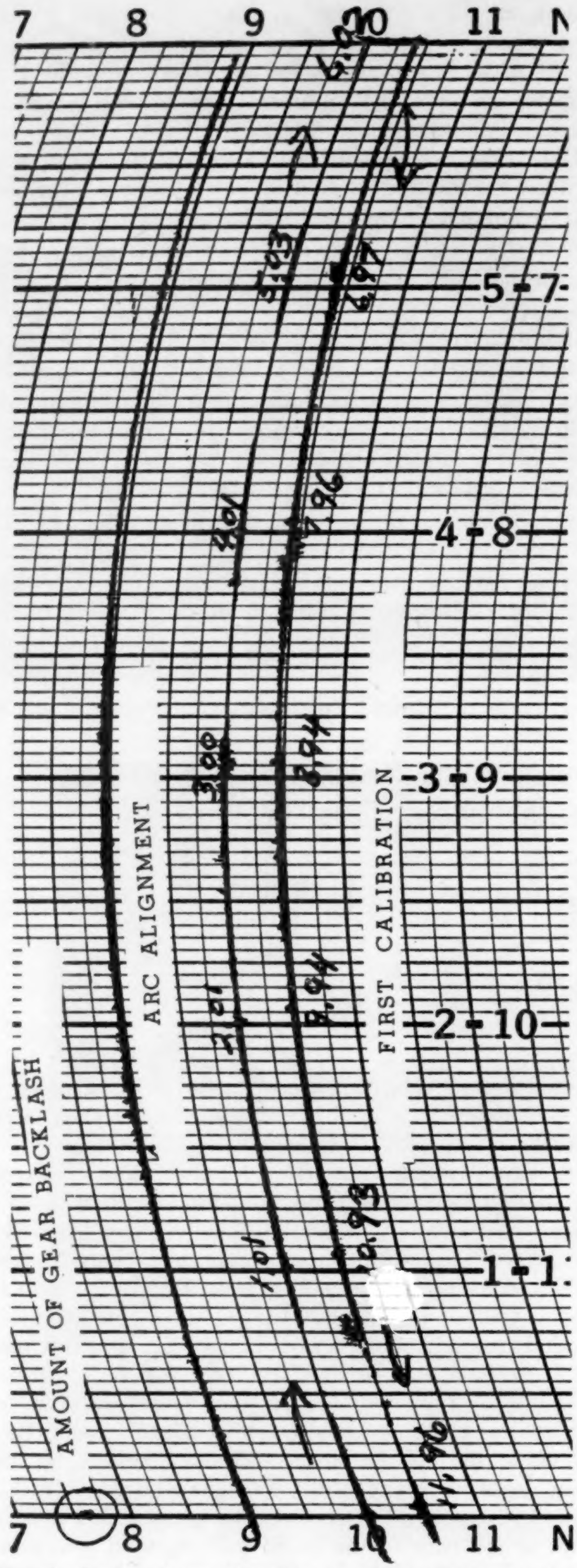

FIGURE 1.—Portion of recording rain gage chart (WB Form 1028C) used on July 11, 1956, in calibration and arc alignment checks of recording rain gage at Unionville, Md.

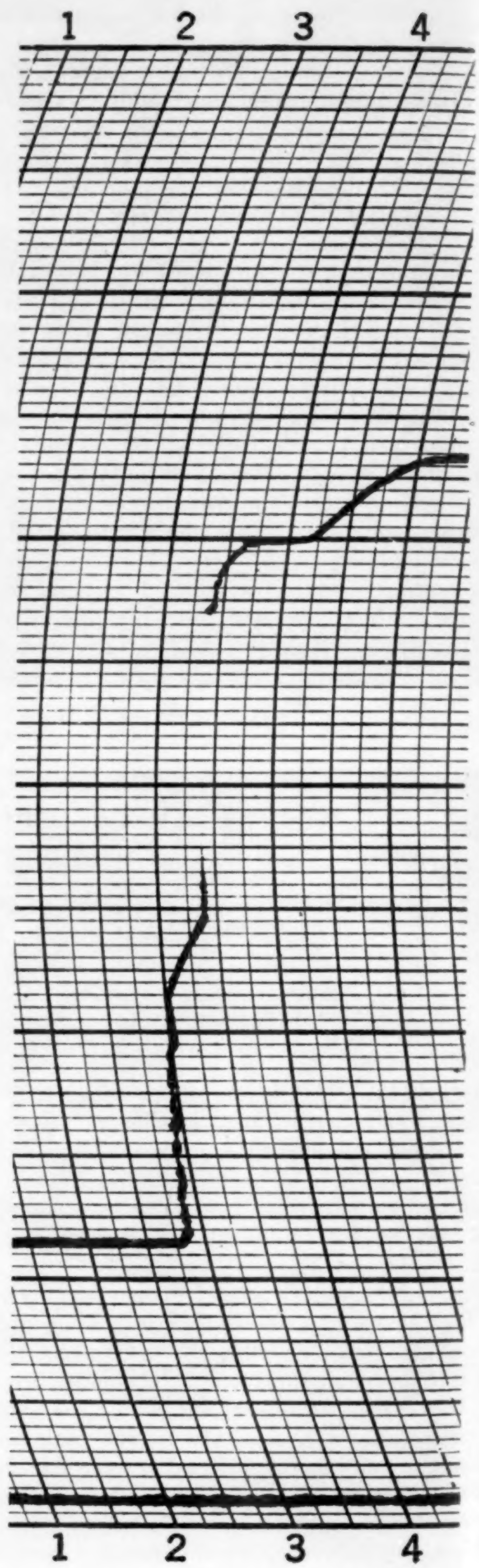

FIGURE 2.—Portion of recording rain gage chart (WB Form 1028C) showing trace of the world-record 1-minute rainfall at Unionville, Md., July 4, 1956.

so heavy that new gutters and downspouts installed on a warehouse were almost useless as water poured off the roof like the "Niagara Falls". The Unionville rainstorm was reported as the worst since May 21, 1942 when a total of 2.90 inches of rain occurred in one hour from 1800 to 1900 EST and a total of 4.80 inches for the 24-hour period ending at 1700 EST May 22, 1942 as reported by Mr. Von Eiff.

The 1.23-inches-in-1-minute rainfall was measured with a recording rain gage. The gage, a Friez Universal Type, 12-inch capacity, dual traverse pen, and 24-hour clock gear with WB Form 1028C on chart drum, is located in a satisfactory exposure. A few low trees grow near the gage to the southwest but do not interfere with the exposure. The station is near the bank of a creek which drains a small watershed. Taller trees and buildings generally surround the station area at a distance of 75 to 100 feet or more and provide an exposure more or less sheltered from strong winds.

The following points which could have contributed to an error were considered in evaluating this record: 1. Can a 1-minute time interval be measured on chart WB Form 1028C? 2. Was the clock operating properly? 3. Could the clock have stopped momentarily and then started again? 4. Was the clock taking up backlash during this period? 5. Could a bug have gotten in the clock gears and briefly stopped or delayed forward motion? 6. Could the pen have stuck momentarily on the chart? 7. Could a leaf or other object have closed the opening in the receiver until a buildup of water forced it through the opening? 8. Was the gage in proper calibration for scale and for arc? 9. Was there any defect in the linkage or bearings of the gage mechanism which might account for the pen failing to rise properly during the period of heavy precipitation? 10. Was the chart seated properly on the flange of the clock drum? 11. Could the chart have expanded due to dampness or high relative humidity? 12. Was the clock properly seated on the spindle and completely at the lowest point? 13. Could a gust of wind have jolted the gage and clock to give the gears backlash?

There are, no doubt, other sources for error which might have been considered. However, in order to make some attempt to evaluate the record in the light of the items listed above, the State Climatologist (one of the authors: H. H. E.) and Thomas E. Hostrander, Substation Inspector, made a trip to Unionville late on the 6th to make a preliminary survey of conditions before the memory of residents had dimmed and water marks and the condition of the rain gage had a chance to change appreciably. The gage was checked by pouring in a measured quantity of water. No error in calibration was noted. Standard weights were not available at the U.S. Weather Bureau, Baltimore, Md., as the inspector's truck was in a garage in a nearby city. The gage was found to be in generally good condition; however, it was noted that the flood waters had risen and flooded the recording rain gage up to the 0.90-inch level of the chart. The clock had stopped at 2330 EST July 4, 1956 according to the chart. This may have been due to the effect of the water rising in the clock mechanism. The record rainfall, however, had occurred well before the flood water had come up into the gage. From the appearance of the chart and the time marks on the chart, the clock was operating on time. There was no reason to suppose that it had stopped during the period of heavy rain. The observer, who was out of town during the rainstorm, estimated that he returned to Unionville at 1955 EST; he checked the gage and made a time check mark at about 2003 EST.

On July 11, 1956 the Substation Inspector visited the station again and performed a more thorough inspection of the recording rain gage as well as a complete calibration and check for arc alignment. A calibration using standard weights indicated that the gage was registering correctly between chart scale amounts of 2.00 and 4.00 inches. A check for arc alignment revealed in the traverse from the zero line to the 6-inch line a time regression of about 6 minutes, or an average of 1 minute per 1 inch on the precipitation scale (fig. 1). The pen trace on the chart for the "1-minute" intensity was rather faint but seemed to regress very slightly with respect to the arc lines of the chart, based on a careful inspection through a magnifying glass (fig. 2). This was interpreted as slight forward motion, estimated at not over 1 minute. From the character of the pen trace during the "1-minute period" it did not seem likely that the pen had stuck to the chart. During the checking and calibration routine, however, the Substation Inspector reported that the pen had stuck on the chart. An inspection of the chart used for checking indicates a fuzzy or scratchy pen trace which was not evident on the record chart. The character of the pen trace on a specimen of chart where the pen had stuck appeared as an ink-soaked spot at the place where the pen stuck followed by a blank space and then another spot-type mark again where it stopped. It is doubtful if this check proved anything.

The inspector poured measured quantities of water into the gage at given time intervals of 30 seconds, 1 minute, 1½ minutes, and 2 minutes. The faint character of the pen trace during the "1-minute rainfall" resembles the pen trace for the simulated 30-second and 1-minute periods in which 1.24 inches of water was poured into the gage. The slope of the arc for the "1-minute rainfall" resembles the test arcs for 30 seconds or 1 minute and 1.24 inches of water. Of course, this does not prove that a piece of lint or other foreign material did not cause ink to flow more from one side of the pen at one point in the traverse as compared with some other point.

In order to make a more precise evaluation of the record a photograph of the chart was enlarged to a scale in which 1 inch of precipitation on the chart scale equals 2.98 linear inches and 1 hour of chart time equals 1.45 linear inches. A careful measurement with a magnifying glass and engi-

neer's scale on the enlarged print of the chart revealed that at chart time of 3:23+ (1523 EST) the pen was at 2.47 inches on the chart scale; at chart time 3:23− (1523 EST) the pen was at 3.70 inches. Based on a regression of 1 minute per inch of precipitation on the chart scale but no correction in calibration of the precipitation scale between 2.00 inches and 4.00 inches it is concluded that 1.23 inches of precipitation occurred in an estimated period of 1 minute or less. See figures 1 and 2.

A 1-minute intensity of 1.23 inches exceeds the intensity of 0.69 inch in 1 minute reported for Jefferson, Iowa [1]. Further, the Unionville record 1-minute rainfall does not appear to be incompatible with an extrapolated envelope curve on Jenning's [2] graph of world's greatest observed rainfalls. There is insufficient evidence to indicate that the possible sources of error operated to make the estimated amount erroneous. These same factors were at least as important and at least as difficult to evaluate in other reports of 1-minute intensities. Consequently, the Weather Bureau has accepted the 1.23 inches as a new United States record for a 1-minute period, which also makes it a new world record.

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SURFACE FRICTION IN A HURRICANE

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ABSTRACT

In an extension of earlier work by Johnson, it is found that the apparent friction of the wind over Lake Okeechobee, Fla., in the 1949 hurricane is related to the speed by $F_s=0.022V^2$ and $F_n=0.020V^2$. F_s and F_n are the frictional accelerations in mi. hr.$^{-2}$ tangential and normal to the wind, and V is the anemometer-level wind speed in m.p.h. Frictional accelerations over land are about three times the over-water values at the same wind speed. At a given storm radius the land and water tangential frictional accelerations are nearly equal.

LIST OF SYMBOLS

V_s=wind speed, always positive.
t=time.
s=distance along streamline; also direction tangent to streamline, positive in direction of wind.
n=direction normal to s, positive to right of the wind.
θ=angle between tangent to streamline and tangent to circular isobar, positive for inward incurvature.
α=specific volume.
p=pressure.
r=distance between the center of concentric isobars and any point, positive outward.
R_t=radius of curvature of trajectory.
f=Coriolis parameter.
F_s=frictional force* tangent to trajectory, positive opposite the wind.
F_n=frictional force* normal to trajectory, positive to right of the wind.
V_H=speed of forward motion of storm.
ψ=azimuth of any point in storm from the storm center, measured from direction of motion of storm with clockwise rotation being positive.

1. INTRODUCTION

This paper is a sequel to an earlier paper by Johnson [1]. He computed the apparent frictional retardation of the wind in the hurricane that passed over Lake Okeechobee, Fla. on August 26–27, 1949. Unusually detailed wind and pressure observations were obtained by the Corps of Engineers network at the Lake and were analyzed by the U.S. Weather Bureau [2]. An important feature of the data is that wind speeds were measured over the water, by anemometers installed on navigation light pylons, as well as from shore stations.

Johnson's method was to compute values from the data for all terms in the equations of horizontal motion except the friction terms and thereby calculate these as residuals. His friction values are mean values for the storm, partly over land and partly over the Lake. This derives from his use of mean radial wind profiles based on all the wind observations, some over water, and some at the shore, with both off-water and off-land wind directions.

In the present study the Lake Okeechobee hurricane data have been reworked by Johnson's method, separately for over-water winds and off-land winds. It was found that the over-water friction components are about proportional to the square of the wind speed. The over-water values are probably the best available estimates of the low-level frictional forces in a hurricane over a water surface.

2. EQUATIONS OF MOTION

Stationary storm.—The equation of motion along any horizontal streamline in a stationary, circularly symmetrical storm is:

$$\frac{dV_s}{dt}=-V_s\frac{\partial V_s}{\partial r}\sin\theta=\alpha\frac{\partial p}{\partial r}\sin\theta-F_s. \quad (1)$$

The respective terms give the total acceleration along the streamline or trajectory, the acceleration in terms of the wind speed and wind speed gradient, the component of pressure gradient force along the streamline, and the frictional force along the streamline. The directions involved in this equation and the next equation below are illustrated in figure 1.

The corresponding equation for acceleration normal to the streamline or trajectory is:

$$\frac{V_s^2}{R_t}=\frac{V_s^2}{r}\cos\theta-V_s^2\frac{\partial\theta}{\partial r}\sin\theta=\alpha\frac{\partial p}{\partial r}\cos\theta-fV_s-F_n. \quad (2)$$

Here the first term on the left is the centrifugal force. The next two terms express the centrifugal force in two parts, that which must be overcome to maintain a constant θ along the streamline and that which must be overcome

*Throughout this paper the term "force" means force per unit mass.

to increase θ. The final three terms are the component of the pressure gradient force normal to the streamline, the Coriolis force, and the frictional force normal to the streamline, respectively.

Equations (1) and (2) are the equations that were used by Johnson [1]. The next subsection will justify the application of equations (1) and (2) for a stationary storm to the storm of August 26–27, 1949 which was moving about 16 m.p.h.

Moving storm.—Equation (1) is a special case of the following more general equation for the central part of a moving hurricane in which an unvarying circularly symmetrical pressure field moves forward in a straight line at a fixed speed. The wind field is not necessarily symmetrical but is fixed with respect to the center; that is, the pattern of isogons and isotachs moves forward with the speed of the storm but otherwise remains unchanged.

$$\frac{dV_s}{dt}=-\frac{\partial V_s}{\partial r}(V_s \sin \theta+V_H \cos \psi)+\frac{1}{r}\frac{\partial V_s}{\partial \psi}(V_H \sin \theta - V_s \cos \psi)=\alpha\frac{\partial p}{\partial r}\sin \theta-F_s. \quad (3)$$

Equation (3) is derived by expansion of the derivative dV_s/dt. As wind speed under the stated restrictions is a function of r and ψ only, by the rules for expansion of derivatives,

$$\frac{dV_s}{dt}=\frac{\partial V_s}{\partial r}\frac{dr}{dt}+\frac{\partial V_s}{\partial \psi}\frac{d\psi}{dt}. \quad (4)$$

Here dr/dt is the total time rate of change of the distance from the storm center to an air parcel. But

$$\frac{dr}{dt}=\left(\frac{dr}{dt}\right)_1+\left(\frac{dr}{dt}\right)_2 \quad (5)$$

where $(dr/dt)_1$ is the rate of change of length r due to the motion of the air parcel and $(dr/dt)_2$ is the change in r due to the motion of the storm center.

From the geometry of the model,

$$\left(\frac{dr}{dt}\right)_1=-V_s \sin \theta;\ \left(\frac{dr}{dt}\right)_2=-V_H \cos \psi \quad (6)$$

or

$$\frac{dr}{dt}=-V_s \sin \theta-V_H \cos \psi. \quad (7)$$

By similar reasoning,

$$\frac{d\psi}{dt}=\left(\frac{d\psi}{dt}\right)_1+\left(\frac{d\psi}{dt}\right)_2=-\frac{V_s}{r}\cos \theta+\frac{V_H}{r}\sin \psi. \quad (8)$$

Substituting (7) and (8) in (4) gives:

$$\frac{dV_s}{dt}=-\frac{\partial V_s}{\partial r}(V_s \sin \theta+V_H \cos \psi)+\frac{1}{r}\frac{\partial V_s}{\partial \psi}(V_H \sin \psi-V_s \cos \theta). \quad (9)$$

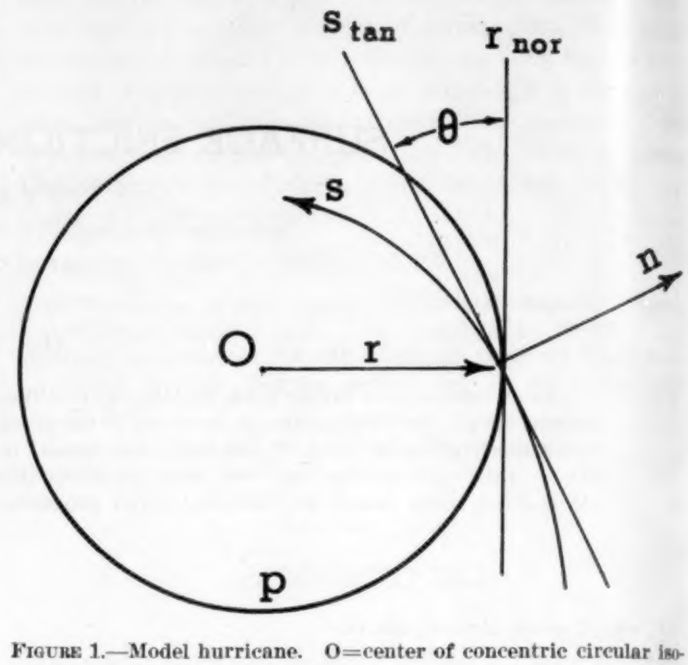

FIGURE 1.—Model hurricane. O=center of concentric circular isobars; p=isobar; s=streamline; s_{tan}=tangent to s; r=radius from O to point on s; r_{nor}=normal to r; n=normal to s; θ=deflection angle between r_{nor} and s_{tan}.

The terms $\alpha(\partial p/\partial r)\sin \theta-F_s$ are the same in equations (1) and (3).

The data most readily available for this study were average values of pressure, wind speed, deflection angle, and radial gradients of these meteorological elements along respective radii. Averaging each term of equation (3) over azimuth, at any one radius, yields:

$$\overline{\frac{dV_s}{dt}}=-\overline{\frac{\partial V_s}{\partial r}V_s \sin \theta}-\overline{\frac{\partial V_s}{\partial r}V_H \cos \psi}+\frac{1}{r}\overline{\frac{\partial V_s}{\partial \psi}V_H \sin \theta}-\frac{1}{r}\overline{\frac{\partial V_s}{\partial \psi}V_s \cos \psi}=\alpha\overline{\frac{\partial p}{\partial r}\sin \theta}-\overline{F_s}. \quad (10)$$

As the fluctuation of the various variables with azimuth is relatively modest, equation (10) can be approximated by:

$$\frac{\overline{dV_s}}{dt}=-\frac{\partial \overline{V_s}}{\partial r}(\overline{V_s}\sin \bar{\theta}+V_H\overline{\cos \psi})+\frac{1}{r}\frac{\overline{\partial V_s}}{\partial \psi}(V_H \sin \bar{\theta}-\overline{V_s}\,\overline{\cos \psi})=\alpha\frac{\partial p}{\partial r}\sin \bar{\theta}-\overline{F_s}. \quad (11)$$

If the average is over 360° rather than only one sector,

$$\overline{\cos \psi}\equiv 0;\ \frac{\overline{\partial V_s}}{\partial \psi}\equiv 0. \quad (12)$$

Equation (11) then reduces to:

$$\overline{\frac{dV_s}{dt}}=-\overline{V_s\frac{\partial V_s}{\partial r}\sin\vartheta}=\alpha\frac{\partial p}{\partial r}\sin\bar{\theta}-\bar{F}_s \qquad (13)$$

which is in the same form as equation (1). The stationary storm equation, (1), if we accept the approximation of product of means equal to mean of products, is applicable, then, to a moving storm, for mean values taken over the entire 360° of azimuth. The last requirement is one reason that no attempt was made to derive separate frictional values for front and rear halves of storm in this study, as did Johnson [1].

The equation of motion normal to the trajectory for a moving storm reduces to equation (2) in the same fashion and under the same restrictions that equation (3) reduces to equation (1).

3. FRICTIONAL FORCES

Observed parameters.—The smoothed mean values of observed pressure and wind used to compute the friction are shown in figure 2. The pressure and wind speed profiles are from [3], the deflection angle from [2], also reproduced in [3]. This interpretation of the deflection angle gives more weight to a few points near the center than does Johnson [1] in his figure 6.

Computation of friction.—Values of the frictional forces, F_s and F_n, were computed for water and for land surfaces at various storm radii by substituting data from figure 2 into equations (1) and (2). Density was fixed at 1.15×10^{-3} gm. cm.$^{-3}$*. The F_s and F_n values are plotted against wind speed on logarithmic scale in figure 3. Most of the points outside the radius of maximum wind speed (23.5 miles) fall approximately in straight lines, suggesting a relation of the form $F=kV^m$. The computed points pertaining to the region inside the radius of maximum winds should be expected to depart from a relation, because the assumption of horizontal trajectories implicit in the method of computing friction probably does not hold across the boundary of the eye.

Relation of friction to wind speed.—Straight lines were fitted by eye to the portion of each set of data outside the radius of maximum winds. The equations of the lines are shown in the upper part of table 1.

The power of V_s for F_s over water was so close to the theoretical value of 2 that it was set equal to this value and k recomputed (lower part of table 1). There is no a priori knowledge of the exponent of V_s in the F_n relation. However, great convenience results in some applications if the exponent is the same for F_s and F_n, as the ratio F_s/F_n then remains constant. For F_n over-water m was also set equal to 2 and the line of best fit with this restriction drawn.

*The horizontal density variation in a hurricane is proportional to the pressure variation. However, speeds were measured with Dines (pitot tube) anemometers, presumably calibrated at normal sea level density, and were not corrected for density. Adjustments to density and wind speed tend to be opposite and compensating and are therefore not required in equations such as (1) and (2), involving specific forces or accelerations.

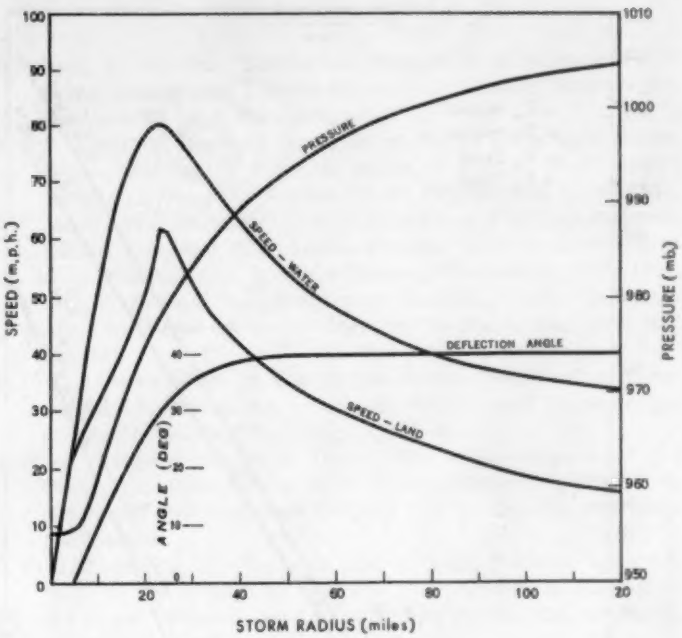

FIGURE 2.—Wind and pressure profiles, hurricane of August 26–27, 1949, at Lake Okeechobee, Fla.

The off-land friction was proportional to about the 1.7 power of the speed. The eye-fitted and adjusted relations are shown in table 1.

Comparison of friction over water and land.—The land values of friction are about three times the water values at the same surface wind speeds (fig. 3). But at the same storm radius *the land and water tangential friction is nearly the same* (fig. 4). This interesting result implies that, at least in this circumstance of a storm partly over land and partly over water, beneath some upper-level wind velocity that is essentially the same over land and water the surface speed adjusts itself to the roughness of the surface such that some requisite frictional retardation is attained.

TABLE 1.—*Relations of friction F_s and F_n to wind speed V_s (see fig. 3)*

Line of best fit by eye	
	Line shown in fig. 3
Over water	
$F_s=0.0195V_s^{2.04}$	No
$F_n=0.0053V_s^{1.87}$	Yes
Over land	
$F_s=0.29V_s^{1.8}$	Yes
$F_n=0.15V_s^{1.8}$	Yes
Smoothed to common exponent	
Over water	
$F_s=0.022V_s^2$	Yes
$F_n=0.020V_s^2$	Yes
Over land	
$F_s=0.20V_s^{1.7}$	No
$F_n=0.21V_s^{1.7}$	No

F_s=frictional acceleration, mi. hr.$^{-2}$, opposite wind vector. F_n=frictional acceleration, mi. hr.$^{-2}$, to right of wind vector. V_s=wind speed, m.p.h.

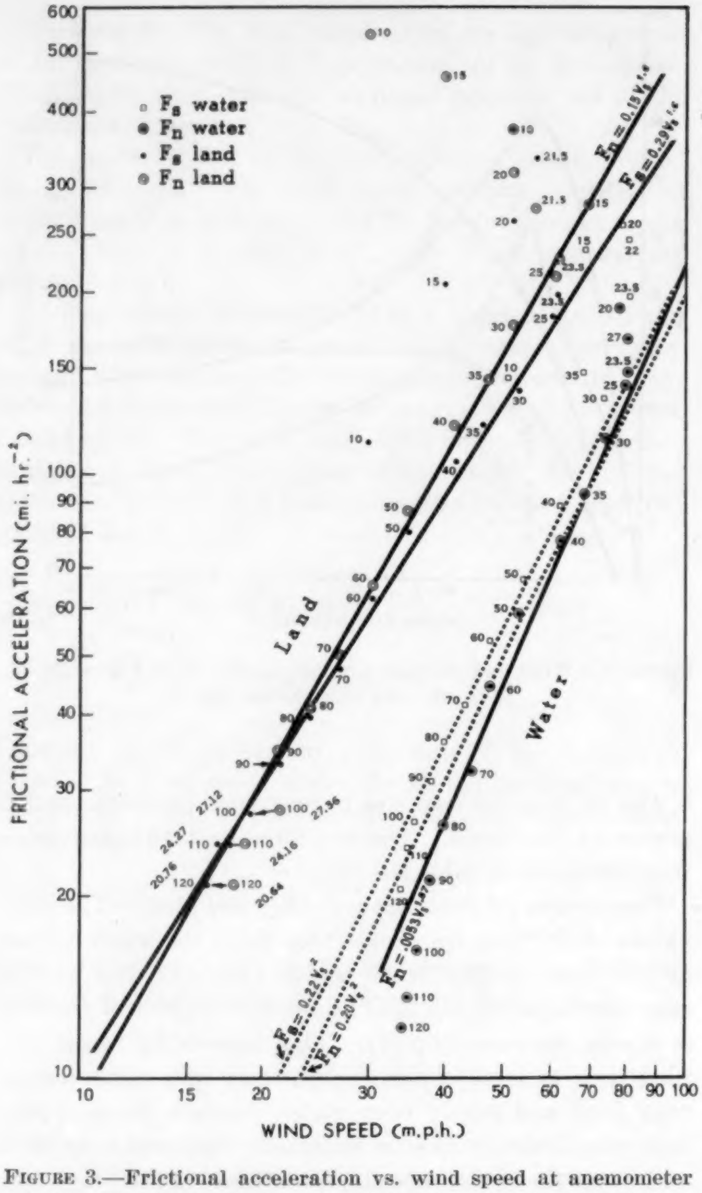

FIGURE 3.—Frictional acceleration vs. wind speed at anemometer level. Hurricane of August 26–27, 1949, at Lake Okeechobee, Fla. Numbers beside points are storm radius in miles.

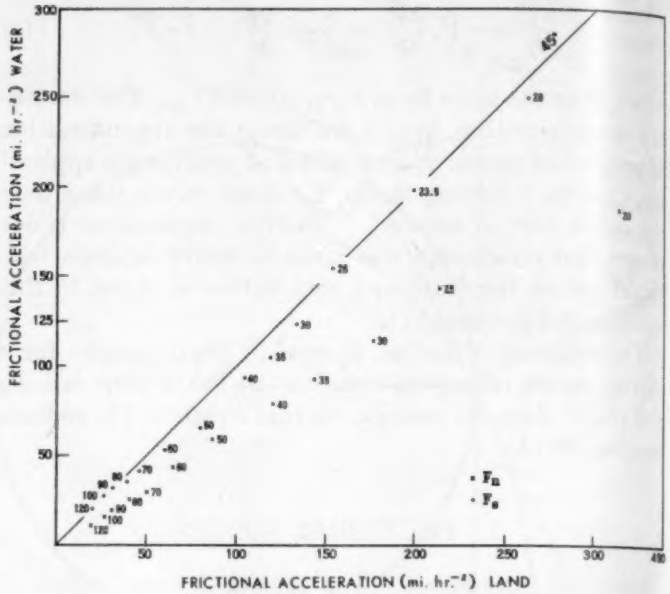

FIGURE 4.—Comparison of frictional accelerations over water and land at same storm radius. Hurricane of August 26–27, 1949, at Lake Okeechobee, Fla. Numbers beside points are storm radius in miles.

The land normal friction is about 50 percent greater than the over-water friction at the same distance from the storm center.

Comparison with other authors' results.—Johnson's [1] values, derived from the same storm but with mixed frictional category, naturally lie between the values derived in this study (fig. 5). In addition to over-water and off-land winds, Johnson includes the "off-water" category of winds (measured at shore stations, wind direction off the lake) which were not used at all in the present study. Hubert [4] has measured friction in other recent hurricanes by similar techniques. The higher wind speeds of his investigation overlap the lower speeds of this study. Comparisons with some of his values are shown in figure 5. Hubert's values are lower, his over-land values being approximately the same as the over-water values of this study for given wind speeds.

Analyses of the friction of the surface wind elsewhere than in hurricanes have also shown large values of normal component of friction [4, 5, 6, 7].

4. SUMMARY

Some detailed observations from a hurricane passing over a lake have been analyzed to determine the apparent frictional force on the anemometer-level wind flow. The component of friction to the right of the wind was about equal to the component opposite the wind over land, and almost as large over water. Outside the eye of the storm and in over-water flow both components were nearly proportional to the square of the wind speed. The winds appeared to adjust themselves in such a way that the total friction of the anemometer-level wind was about the same at any storm radius over water and over land.

The relations found can be used for estimates of the friction of the low-level wind in hurricanes at sea, though the questions remain of the relative roughness of the ocean as compared with Lake Okeechobee and of variations due to differences in structures of individual storms.

ACKNOWLEDGMENT

The over-water friction value computations were taken, in part, from a related study by Herman Lake [8].

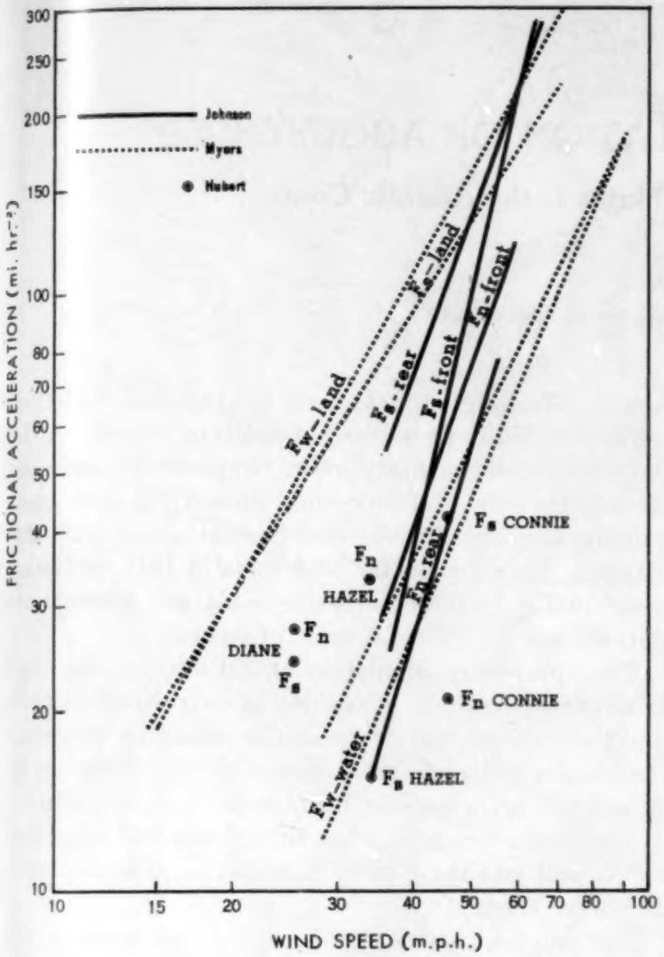

FIGURE 5.—Comparison of computed frictional accelerations. Johnson [1]: hurricane of August 26–27, 1949, at Lake Okeechobee, Fla. Values stratified into front and rear of storm but mixed as to category of underlying surface. Myers: same hurricane, from figure 3. Values stratified into over-water and off-land but mixed as to azimuth. Hubert [4]: selected hurricanes 1954–55, over land, mixed azimuth.

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THE WEATHER AND CIRCULATION OF AUGUST 1959

A Hot Month from the Central Plains to the Atlantic Coast

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1. THE HEAT WAVE IN RELATION TO THE CIRCULATION

August 1959 was an exceptionally hot month for most of the United States. Figure 1 shows that in about three-fourths of the country, monthly temperatures averaged warmer than the seasonal normal. From the Dakotas to the Lower Great Lakes and from the Ohio Valley to the Middle Atlantic States, temperatures averaged from 4° to more than 6° above normal for the month. Cooler than normal weather was confined principally to a patch in the Southern Plains States and to a belt extending from the Pacific Northwest to parts of the southwestern deserts.

Extremely high temperatures did not typify this August's heat wave, but its severity was manifested in other ways. It is best described as one with successive days of discomfort in which maximum temperatures hovered around 90°F., while humidities and nighttime minimum temperatures were both high.

All-time records for number of days with a maximum of 90°F. or more were reported by Cincinnati, Ohio (22 days), Newark, N.J. (15 days), and Boston, Mass. (11 days). Washington, D.C., and Los Angeles, Calif. airports recorded their warmest Augusts of record. At Los Angeles airport monthly mean temperatures have been warmer than the 1921–50 normal since April 1956, a noteworthy climatic fluctuation. Several cities had their warmest August since the heat wave of 1947, and others since 1937. At the other extreme, Miami International Airport had its coolest August of record.

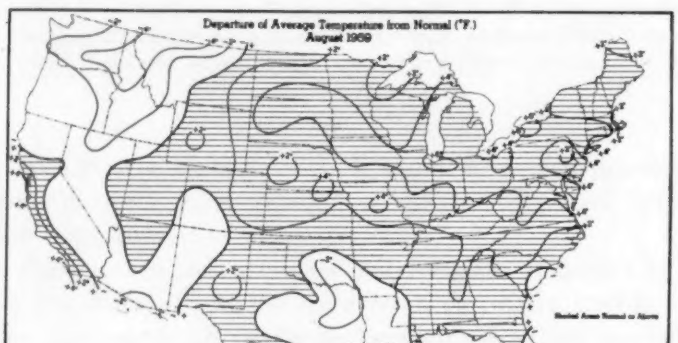

FIGURE 1.—Departure of average surface temperature from normal (°F.), August 1959. Hatching indicates areas of normal or above normal temperatures. Departures of 4° F. or more were common from the Northern Plains to the Atlantic Coast. (From [4] Sept. 7.)

The upper-level circulation at 700 mb. for the month is shown in figure 2. Considering only North America and the adjacent marine areas, the immediate impression is one of a moderate zonal flow with the westerlies displaced well to the north. That condition is not uncommon in the summer months when the subtropical ridge penetrates well into the United States as an extension of the Bermuda High.

The August pattern was generally less complex than that of June [1] or July [2]. The dotted lines in figure 2 represent departures of observed height from normal and thereby show the relative strength of major features. Of considerable importance to the weather in the United States was the lack of amplitude of the wave pattern there. However, the trough in western North America was sufficiently intense to keep the West cooler than normal as the eastern Pacific ridge propelled cool, maritime air into it. Confluence of cool and warm streams of air in central Canada was associated with fast westerlies across Canada, thus precluding strong ridge development north of the United States border. Height departures in the downstream trough off the Atlantic Coast were negative only in its southern portion.

Much of the United States might have been cool instead of hot had there been a mechanism to transport the cool Pacific air deeply into the country. But the combination of the trough in western North America, the ridge in eastern United States, and fast westerlies in Canada was not conducive to the invasion of cool air masses. Even though the ridge was only some 80 feet above normal, its persistence permitted a continuation of warm conditions. The broad southerly flow at sea level (see Chart XI of [3]) supplemented that at the upper level. Its presence

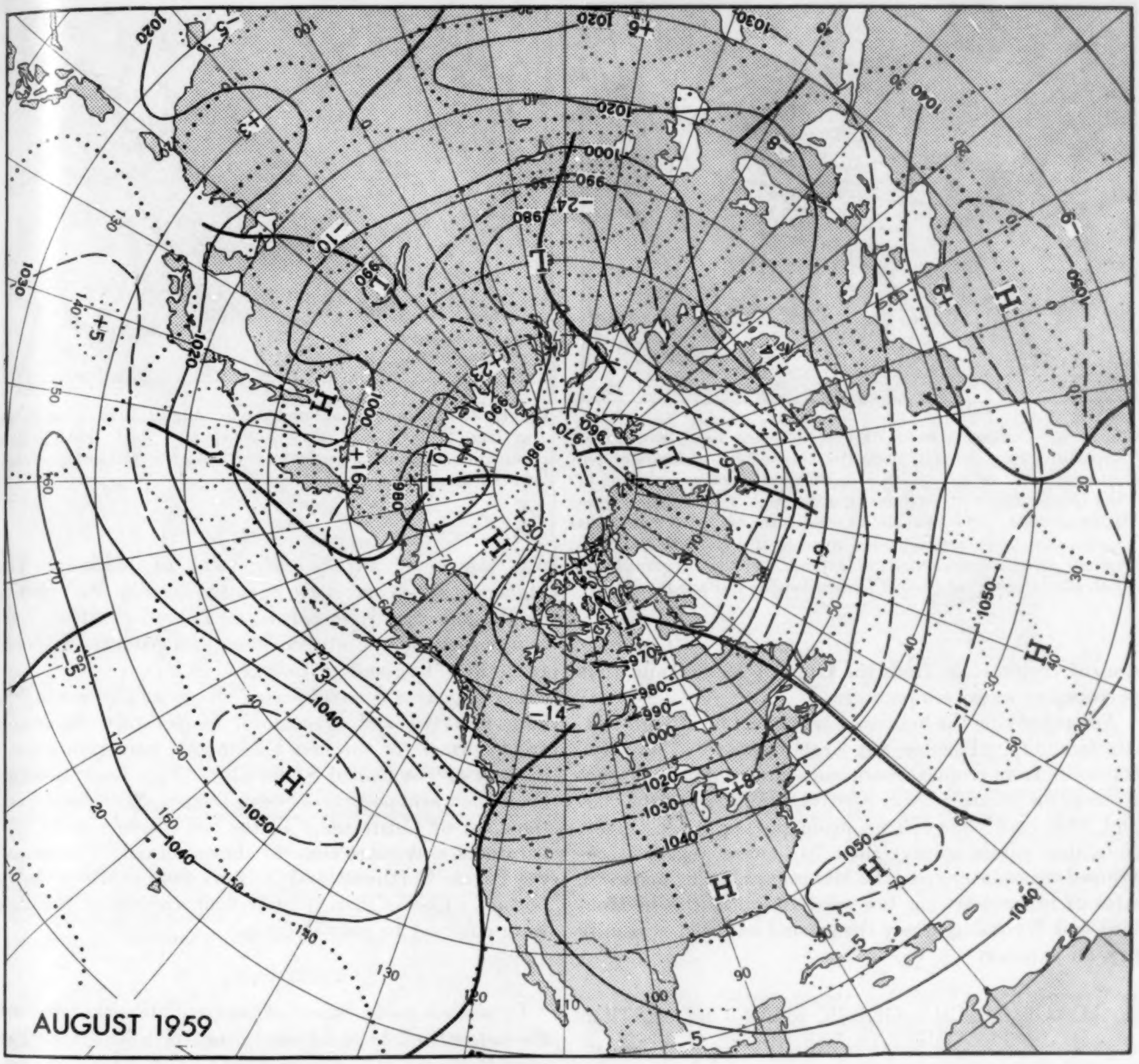

FIGURE 2.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for August 1959. Over the United States and adjacent oceans the westerlies were weak or absent south of 45° N., and the warm, subtropical ridge had a great influence on the weather.

also suggests warming and recurrent thrusts of tropical air east of the Rockies.

Figure 3 is a composite chart prepared from ten cases of heat waves in the northeastern quadrant of the country in June, July, or August selected from the years 1933 to 1958. For this study a heat wave was defined as the predominant occurrence of the much above [1] normal temperature anomaly. In many respects the observed upper-level mean for August 1959 closely approximated the composite (compare figs. 2 and 3).

The composite represents the type of flow in which the polar front may be expected to lie along the northern border of the United States east of the Continental Divide. The absence of a ridge in Canada precludes massive cold advection into the eastern half of the country. The extensive tropical ridge in the southern and central States and the intensified southerly flow insures repeated advec-

[1] Temperature anomalies are divided into the following classes: much above and much below (12½ percent occurrence each) and above, near normal, and below (25 percent occurrence each).

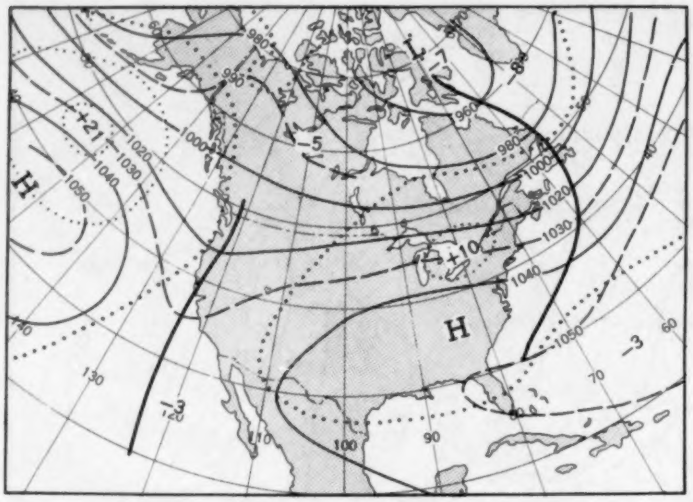

Figure 3.—Composite mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for ten selected cases of hot weather in the northeastern quadrant of the United States for summer months (June, July, August) from 1933 to 1959. The obvious features common to all hot spells in the Northeast are: a strong ridge in the Gulf of Alaska, a trough along the west coast, an extension of the Bermuda ridge into the Midwest, and below normal heights in Canada.

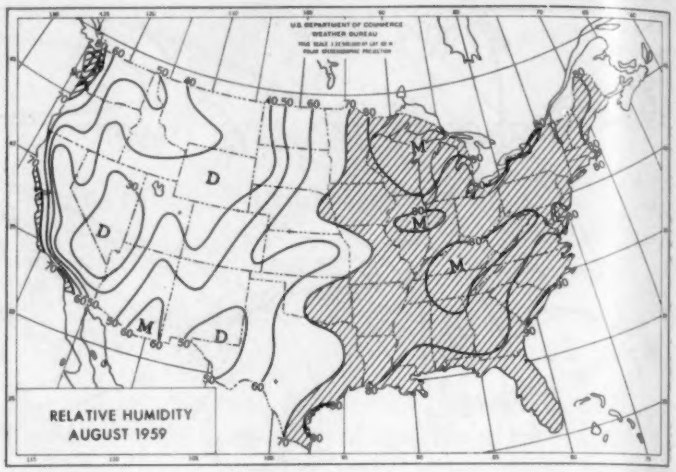

Figure 4.—Mean relative humidity for August 1959 based on the average of 0000 and 1200 GMT values. Very high relative humidities dominated the country from the Mississippi Valley to the Atlantic Coast.

tion of tropical air from the Gulf of Mexico and thus perpetuates warm temperatures.

Accompanying the heat wave was a regime of high relative humidity. This too was largely a result of low-level transport from tropical maritime source regions. Figure 4 shows the monthly mean relative humidities of the 0000 and 1200 GMT observations made during August 1959. Note that values greater than 70 percent (shaded) enveloped the country from the Mississippi Valley eastward. Also of interest are the low relative humidities in Montana and Wyoming, where the ground has been especially dry all summer.

2. EFFECT OF CHANGES IN MEAN CIRCULATION ON TEMPERATURES IN THE UNITED STATES

AUGUST 1–15, 1959

The mean circulation at 700 mb. over the United States during the first half of August was generally quite weak, as shown in figure 5A. Except along the northern border, where moderate westerlies prevailed, the gradient of 700-mb. height was seldom as much as 100 feet. Another feature of the chart, one which sometimes signifies an impending change, is the long wave spacing at 50° N. The next trough upstream from the one over Maine was at 165° W., a distance in excess of 90° of longitude.

The trough along the east coast was of considerable importance to the weather in spite of its small amplitude. Although not too apparent from the contours, this trough was the lower-latitude component of blocking. The higher-latitude component was evidenced by the +220-ft. height departure from normal off Labrador. Thus, easterly onshore flow prevailed along the Atlantic Seaboard from New England to Georgia.

Perhaps as a consequence of the generally weak flow, both observed and anomalous, temperature departures from normal for the first half-month were rather small in most of the United States (fig. 6A). Exceptions include the warm pockets in South Dakota, New Mexico, and the coast of California. In the last instance mean temperatures were more than 6° above normal. Portions of the Pacific Northwest and Arizona were nearly 3° below normal. Cooler than normal temperatures in the East were confined to coastal areas.

AUGUST 16–30, 1959

Broadscale readjustment of the circulation characterized the last half of August in and near North America. Figure 5B shows well-organized centers of action and substantial centers of height departure from normal. Anticyclonic conditions in the Gulf of Alaska replaced the generally cyclonic conditions observed there a half month earlier, with heights rising as much as 480 feet. Associated with this strengthening ridge, a strong trough appeared downstream over the western United States.

Marked cooling became associated with the trough in the West, and widespread heating accompanied intensification of the ridge in the East. The extent of the heating and cooling are portrayed in figure 6B.

Cold air penetrated into the interior valleys of California where temperatures averaged more than 4° below normal, contrasted with 4° above normal during the first

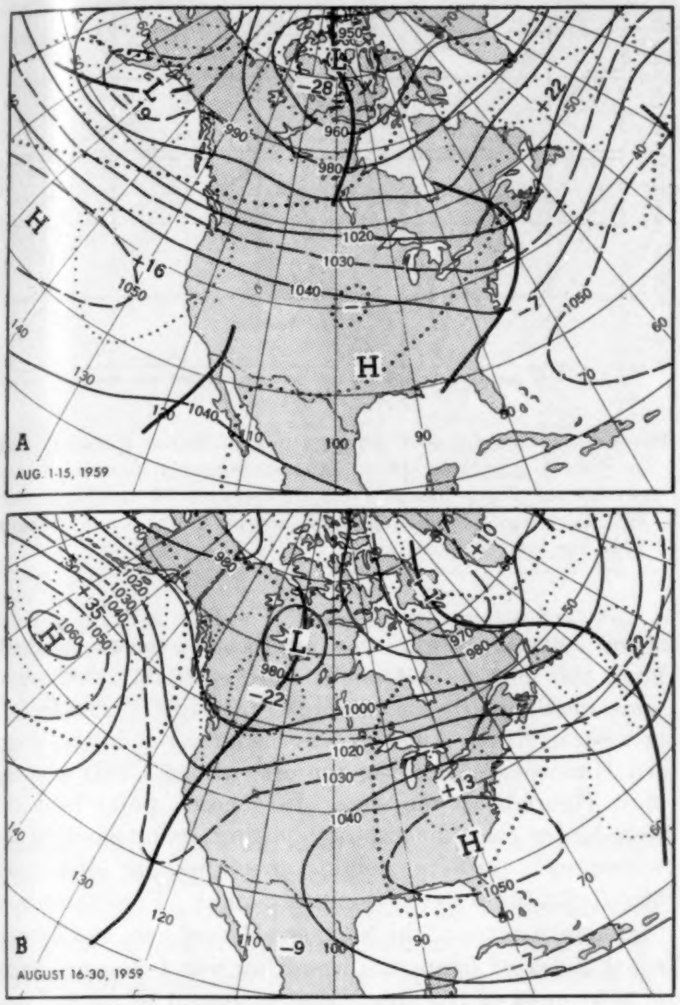

FIGURE 5.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for (A) August 1–15, 1959, and (B) August 16–30, 1959. Note the reversal of the circulation in the eastern Pacific and western North America as amplification occurred in the last half of the month.

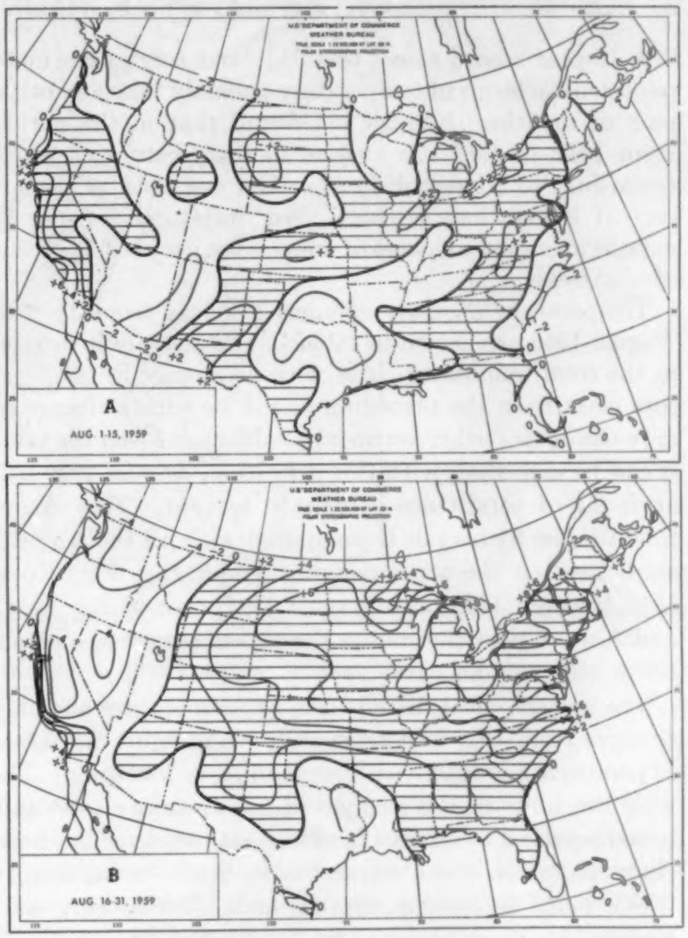

FIGURE 6.—Departure of average surface temperature from normal (°F.) for (A) August 1–15, 1959, and (B) August 16–31, 1959. Hatching indicates areas of normal and above normal temperature anomalies. Warming in the latter half of August was greatest in the eastern Great Lakes, and widespread in other areas east of the Rockies.

half of August. During the week ending August 24, temperatures of 10°–20° F. below normal were responsible for new low daily maximum records [4].

The positive height anomaly center near the lower Great Lakes (fig. 5B) was also the seat of the maximum surface temperature departures from normal (fig. 6B). Lower Michigan and northern portions of Illinois and Indiana recorded mean temperatures for the last half of August greater than 9° F. above normal. It was during this period that Chicago equalled an existing record of 11 consecutive days with 90° F. or above. Cincinnati had only three days out of the last 16 days of August in which the maximum temperature fell below 90° F. The Dakotas had numerous readings above 100° F.—to as high as 112° F. at Vivian, S. Dak.—during the week ending August 24 [4].

No storm centers penetrated the Eastern States from August 16 to 31, thus permitting an uninterrupted heat wave. The principal storm track was near Hudson Bay and was reflected aloft as the channel of negative height departures in that area (fig. 5B).

The temperate westerly index [2] is frequently a satisfactory reflection of the circulation. In August the behavior of the index was reasonably descriptive of the long-wave evolution near North America. The index reached a maximum of 9.1 m.p.s. (the highest since early June) for the 5-day period ending August 15. That was the termination of a generally rising index the first fifteen days of the month. Coincident with amplification of the trough in western North America the index started falling, and by the end of the month reached 4.8 m.p.s., more than 2 m.p.s. below normal.

[2] Computed at 35°–55° N. from 5° W.–175° E.

3. NON-PERSISTENCE OF TEMPERATURE ANOMALIES

A 16-year record shows that July and August are more persistent in terms of temperature anomaly than any other pair of months. Namias [5] found that in the period from 1942 to 1957 the change in temperature anomaly from July to August did not exceed one class at 82 percent of 100 stations in the United States. The other 11 months averaged a change of one class or none in 67 percent of the cases.

Temperature anomaly changes by class from July to August 1959 are shown in table 1. Persistence is defined as the total number of cities with no change in temperature class from the preceding month or with a change of only one class (either warmer or colder). From the table it can be seen that, with this definition, August 1959 had an index of persistence of only 54 percent. This exceptionally low figure can be compared with all the Augusts since 1942 on the accompanying graph (fig. 7). From 1942 through 1958 only August 1947 (hot in the East) and August 1958 (hot in the West) had persistence values below the random curve.

The geographical distribution of temperature anomaly changes from July to August is shown in figure 8. Areas of persistence are those without shading or hatching. The wide hatching depicts changes of two or more classes and, to some extent, is indicative of the heat wave. The four-class change in the Central Plains States is an area in which much below temperature anomalies in July were replaced by much above anomalies in August.

Persistence in temperatures does not necessarily imply a persistence of upper-level pattern. However, a month in which the temperature anomaly is particularly non-persistent is almost always associated with a major circulation change from the preceding month. In the present instance a reversal in circulation in the last half of August (discussed above) was responsible for a change of the whole monthly pattern from July to August.

4. OTHER ASPECTS OF THE CIRCULATION AND WEATHER

Figure 2 shows that the Low in the western Siberian lowland was the only vortex on the map whose monthly

TABLE 1.—*Class changes of surface temperature anomalies in the United States from July to August 1959*

Class change	Frequency (percent)
+4	3
+3	7
+2	18
+1	23
0	22
−1	9
−2	16
−3	2
−4	0

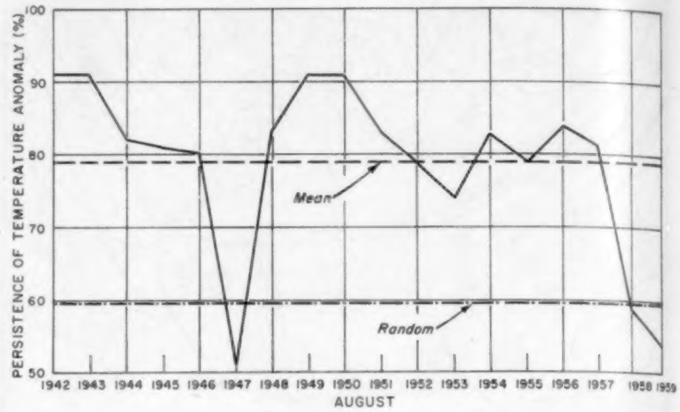

FIGURE 7.—Persistence of temperature anomalies (percent) from July to August 1942–1959. August normally has the highest persistence of any month averaging between 70 and 90 percent. In 1959 August was unusually non-persistent. Only August 1947 was less persistent.

mean 700-mb. height was appreciably below normal. Even the long-wave troughs were relatively weak, and some were actually above normal in height. The trough in western North America was the strongest in the Western Hemisphere, and the one east of the Urals was the most vigorous on the map. In general, polar latitudes were under the influence of blocking, as attested by the widespread positive height anomalies in that area. Middle latitudes were moderately zonal. For example, in the western sector of the Northern Hemisphere, the 700-mb. zonal index of temperate westerlies was 1–2 m.p.s. below normal most of the month and increased to normal near the end of the month.

Although the Tropics were predominantly below normal in 700-mb. height, tropical storms were not especially active. In the North Atlantic (including the Gulf of Mexico and the Caribbean) tropical development was slight in August, as only one tropical depression managed to develop into a tropical storm. An easterly wave strengthened in the Lesser Antilles was designated Edith, then weakened as it moved westward. A week later the easterly wave brought heavy rains to the Texas coast, where the depression first deepened slightly then weakened again as it moved rapidly inland. The probability of tropical storm development in the North Atlantic in August is 1.6 storms per year according to Dunn [6]. (A later computation based on nine more years of data increased the average to 1.8 per year [7]).

On the other hand, in the western North Pacific there was greater than normal tropical storm activity. There has been an average of 4.6 storms per year in August [6], but this year 6 were found. Of those, there were five typhoons and one tropical storm. One hurricane in the eastern North Pacific was destructive on the island of

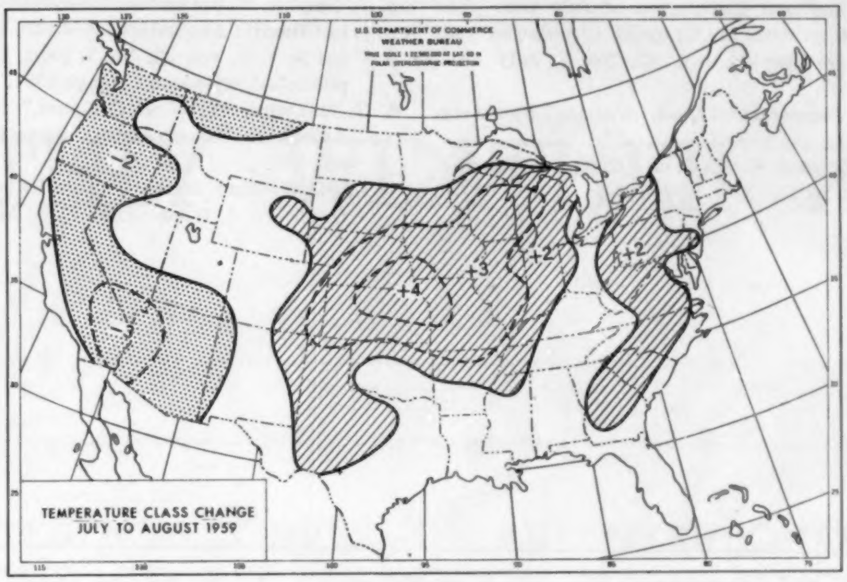

Figure 8.—Change in class of temperature anomalies from July 1959 to August 1959. In unshaded areas temperature anomalies did not change by more than one class; hatched portions represent a warming of two or more classes; and stippled areas denote a cooling of two or more classes. The temperature reversal in the Central Plains States and in Southern California contributed most to the non-persistence of August.

Kauai, Hawaii. Rain at Lihue was 8.13 in. for the month, almost 6 in. in excess of normal.

Precipitation in the United States (fig. 9) not directly attributable to local tropical developments was rather chaotic, but many features could be partially explained by physical considerations implicit in the monthly mean circulation at 700 mb. (fig. 2). For example, rainfall amounts in Oregon and Idaho were as much as three times normal under faster than normal westerly flow in advance of the mean trough lying near the coasts of Washington and Oregon. In a similar manner, upslope cyclonic flow at more northerly latitudes contributed to a total of 10.57 in. of rain at Annette, Alaska, which was more than 5 in. above normal. East of the Continental Divide the westerlies produced foehn drying. In Montana and Wyoming observed precipitation totals were less than 25 percent of the monthly normal (fig. 9) in a large area. Glasgow reported that August was its sixth consecutive month with below normal precipitation [4], and Billings recorded its driest May through August since 1894 [4].

A belt of generally heavy rain extended from the Dakotas to New England, and paralleled the axis of maximum frontal activity in August, along which there were 15–25 days with fronts. Of additional interest is the mean flow (fig. 2) which shows confluence (and thus frontogenesis) in that area, along the boundary between tropical and maritime polar air masses. Note also that mean 700-mb. height anomalies were positive, a condition usually associated with less than normal rainfall. Perhaps more surprising was the liberal distribution of heavy rainfall in many portions of the heat wave zone, since hot weather usually goes with dry conditions.

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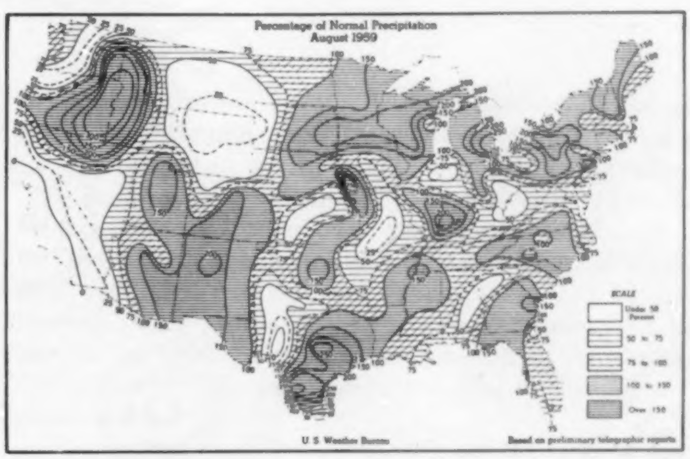

Figure 9.—Percentage of normal precipitation for August 1959. Note the discontinuous nature of precipitation greater than normal which occurred south of the Lakes and east of the Rockies. (From [4] Sept. 7.)

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CORRECTION

Monthly Weather Review, vol. 87, No. 7, July 1959, p. 269: In column 2, first complete paragraph, change −99.9° C. to −90.9° C. The sentence should read, "The lowest temperatures registered during this ascent were: −89.5° C. (−129.1° F.) at 17,000 m. on the way up, and −90.9° C. (−131.6° F.) at 16,500 m. on the way down."

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